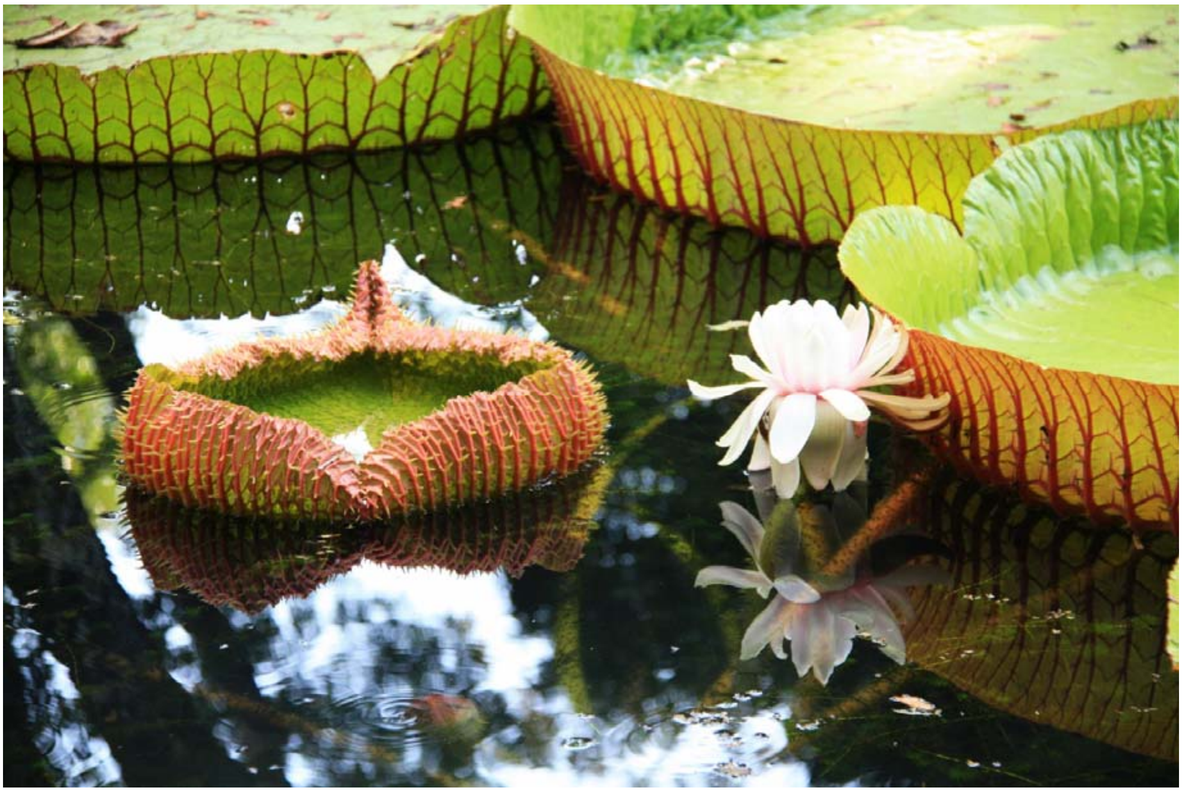
JRC Scientific and Technical Reports

Supporting Environmentally Sound Decisions for Waste Management

A technical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners



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The mission of the JRC-IES is to provide scientific-technical support to the European Union's policies for the protection and sustainable development of the European and global environment.

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Executive Summary

Overview

Environmental protection ranks high in the European public agenda. The waste management sector is therefore expected to reduce its adverse environmental impacts. However, the increasing complexity of current waste management systems and the increasingly demanding environmental protection targets make it challenging to optimise waste management strategies and policies.

The general principles of good management are outlined in the EU Waste Framework Directive (2008/98/EC). In article 4(1), the Waste Framework Directive establishes a straightforward five-step waste hierarchy as legally binding priority order for waste management. Waste prevention is regarded as the most desirable option, followed by preparing waste for re-use, recycling and other recovery, with disposal (such as landfill) as the last resort.

Generally, applying the waste hierarchy should lead to the waste being dealt with in the most resource-efficient way. However, as supported by Article 4(2), Life Cycle Thinking (LCT) can be used to complement the waste hierarchy in order to make sure that the best overall environmental option is identified.

The Life Cycle Thinking (LCT) concept and quantitative tools such as Life Cycle Assessment (LCA) can provide an informed and science-based support to a more environmentally sustainable decision-making in waste management.

To support environmentally sound decision-making in waste management, the Joint Research Centre (JRC) in cooperation with the Directorate General (DG) Environment have developed guidelines tailored to address different target audiences and partly focusing on specific waste streams. These include:

- “Supporting Environmentally Sound Decision for Bio-Waste Management – A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)”;
- “Supporting Environmentally Sound Decision for Construction & Demolition (C&D) Waste Management – A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)”;
- The present document: “Supporting Environmentally Sound Decision for Waste Management – A technical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners”.

About this guidance document

This guide focuses on the most relevant technical aspects that need to be considered when applying Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) to the waste management sector. Main focus is put on the environmental pillar of sustainability. It builds on the International Organization for Standardization (ISO) 14040 and 14044 standards for LCA and the International Reference Life Cycle Data System (ILCD) Handbook.

It is aimed at waste managers, technicians and LCA practitioners, but also provides policy makers with insights and hints on what they need to consider when using LCT and LCA to support policy making in the waste management context.

About Life Cycle Thinking (LCT)

Over their life-time, products (goods and services) contribute to various environmental impacts. Life Cycle Thinking (LCT) is a concept that accounts for the upstream and downstream benefits and trade-offs. LCT seeks to identify environmental improvement opportunities at all stages across the life cycle, from raw material extraction and conversion, through product manufacture, product distribution, use and fate at the end-of-life stage. Its fundamental aim is to provide a structured and comprehensive approach in support of the overall reduction of product impacts and to help optimise benefits.

LCT helps to avoid resolving one environmental problem while creating others (i.e., resulting in the shifting of burdens). It helps to avoid, for example, improving production technologies while causing waste-related impacts, reducing emissions of greenhouse gases while increasing land use or acid rain, or reducing emissions in one country while increasing them in another.

About Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a structured and internationally standardised method that transposes Life Cycle Thinking (LCT) principles into a quantitative framework. LCA quantifies all relevant emissions, resources consumed/depleted, and the related environmental and health impacts associated with any goods or services. Therefore, within the concept of LCT, LCA is a vital and powerful tool to effectively and efficiently help make consumption and production globally more sustainable.

When LCT/LCA are applied to waste management services, typically the assessments focus on a comparison of different waste management options, not covering the entire life cycle of the products which have become waste. Therefore, LCT/LCA applied to waste management services can differ from product LCT/LCA. Product LCT/LCA accounts for the entire life cycle of a product, in which waste management may play only a minor role. However, if one of the evaluated waste management options includes that materials are given back into the life cycle of a product, a product life cycle perspective has to be taken into account also in LCT/LCA for waste management services.

Approach and key issues addressed in this document

This document provides guidance on how LCT and LCA can be used to help identify the preferable environmental option amongst alternative waste treatment technologies, scenarios, etc. In particular, the document provides guidance on how to:

- Gain a good understanding of the problem and to determine whether LCT and LCA can help address the issue;

- Develop straightforward LCT-based criteria to address waste management issues in simple, day-to-day decision-making;
- Conduct new LCAs in case where this is seen as necessary to identify the overall best environmental option;
- Develop waste-specific management planning to favour consistent and robust implementation of LCT and LCA into the waste management sector;
- Identify key indicators for waste; identify relevant waste treatment technologies and management options; group waste types based on their characteristics;
- Develop simplified, user-friendly LCA software tools for users who may not have a strong background on LCA.

Target audience

This guide has been developed for experts in the field of waste management and environmental assessment, both on a technical level and on the level of policy making. This includes, for instance, companies, public authorities, business associations, consultancies and research centres.

Remarks

This document focuses on the environmental aspects of waste management services. While economic, social/societal aspects are mentioned, no detailed guidance on how to include them is provided.

The recommendations given in this document are intended to help model a limited set of typical waste management and treatment activities, focussing on those processes, parameters and impacts that typically matter most. However, the LCA/LCT results and conclusions cannot be generalised and it is the responsibility of the expert to judge whether existing studies and information are relevant and can thus be extrapolated to a new situation not covered in this LCA/LCT study.

Links to specific chapters of the ILCD Handbook provided in this guidance refer to the current edition of the ILCD Handbook (Edition 1).

List of key abbreviations

BAT	Best Available Technology
CBA	Cost Benefit Analysis
C&D	Construction & Demolition
CHP	Combined Heat & Power
EMC	Environmentally weighted Material Consumption
EMS	Environmental Management System
GHG	Greenhouse gas
FGC	Flue Gas Cleaning
ILCD	International Reference Life Cycle Data System
ISO	International Standardization Organization
KEDMA	Key Environmental Data and Modelling Assumption
KEPI	Key Environmental Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LFG	Landfill gas
MBT	Mechanical Biological Treatment
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
SLCA	Social Life Cycle Assessment
WFD	Waste Framework Directive
W-t-E	Waste to Energy (i.e., waste incineration with energy recovery)

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1 Introduction

What is the focus of this chapter?

This chapter provides an introduction to this guidance document and its structure, use, and application. The general background, the objectives and the target audience are also briefly presented.

Who should read it?

Anyone looking for relevant information on Life Cycle Thinking & Assessment, and practical guidance on how to apply them in the waste management context.

1.1 Background

Environmental protection ranks high in the European public agenda. The waste management sector is therefore expected to reduce its adverse environmental impacts. However, the increasing complexity of current waste management systems and the increasingly demanding environmental protection targets make it challenging to optimise waste management strategies and policies.

In the area of Waste Management, the general principles of good management are outlined in the EU Waste Framework Directive (WFD) (Directive 2008/98/EC)[1]. In Article 4(1), the WFD establishes the "waste hierarchy" a legally binding priority order of waste management starting with the preferred option of waste prevention, followed by preparing waste for re-use, recycling, other recovery, and disposal (such as landfill) as the last resort. Article 21(1) of the WFD states that waste management planning has to be done in line with the waste hierarchy.

Generally, applying the waste hierarchy should lead to the waste being dealt with in the most resource-efficient way. However, in specific circumstances and for specific waste streams, deviating from the hierarchy may be necessary in order to select the best solution for the environment. Also, in many cases, a number of alternatives exist at a given level of the waste hierarchy (e.g., different recycling alternatives for a given waste stream). However, these alternatives are frequently not equivalent from an environmental perspective.

In order to provide informed and science-based support for environmentally sustainable policy-making in waste management, new approaches are needed which help to identify preferable waste management options and to complement existing waste management insights. Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) can be used for this purpose, respectively as a concept and a quantitative tool to help support decision-making in a scientifically robust manner.

[1] Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0098:EN:NOT

Life Cycle Thinking can be used to complement and refine the waste hierarchy for decision support in waste management. As stated in Article 4(2) of the WFD (see Chapter 3.1) the ultimate goal of the Member States for waste management shall be to identify and implement the environmentally preferable option; to reach this objective, it may sometimes be necessary to depart from the hierarchy if, and only if, this is validated by Life Cycle Thinking.

When LCT/LCA are applied to waste management services, typically the assessments focus on a comparison of different waste management options, not covering the entire life cycle of the products which have become waste. For example, when evaluating different options for bio-waste management, usually the production stages of the food that has become bio-waste, are not considered. Therefore, LCT/LCA applied to waste management services can differ from product LCT/LCA, which accounts for the entire life cycle of a product, in which waste management may play only a minor role. However, if one of the evaluated waste management options includes that materials are given back into the life cycle of a product, a product life cycle perspective has to be taken into account also in LCT/LCA for waste management services. For example, when looking at municipal waste management including recycling, the benefits of saving virgin raw materials in the production stages of products have to be taken into account.

1.2 Objectives

This guide focuses on Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) applied to the waste management sector. It provides guidance on how LCT and LCA can be used to identify the best solution for the environment among alternatives. It expands the International Standards Organization guidelines for LCA (ISO 14040 and 14044)[2] and International Reference Life Cycle Data System (ILCD) Handbook[3] provisions and precise the way to apply them for LCA in waste management. The primary target audience is waste managers, technicians and LCA practitioners. The Guide also provides policy-makers with insights and hints on what they need to consider when using LCT and LCA in decision support for policy making in the waste management context.

In particular, the document provides guidance on how to:

- Gain a good understanding of the problem and assess whether LCT and LCA can help address the issue;
- Develop and use straightforward, LCT-based criteria to address waste management issues in simple, day-to-day decision-making;
- Develop simplified, user-friendly LCA software tools for users who may not have a strong background on LCA;

[2] Available online at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54854
[3] Available online at http://lct.jrc.ec.europa.eu/publications

- Apply LCA to support decision-making;
- Develop waste-type specific management planning to ensure consistent and robust implementation of LCT and LCA in waste management;
- Identify key indicators for waste, relevant waste treatment technologies and management options, and group waste types based on their characteristics.

1.3 Structure of this document

This document is structured into nine chapters:

- **Chapter 2 (Why Use Life Cycle Thinking and Assessment in Waste Management Decision Support)** provides an introduction to Life Cycle Thinking (LCT), Life Cycle Assessment (LCA) and a number of other widely used LCT-based methods for waste management
- **Chapter 3 (Complementing the Waste Hierarchy with a Life Cycle Thinking)** describes the steps of the waste management hierarchy (prevention, preparing for re-use, recycling, other recovery and disposal) and explores how LCT and LCA can be used to complement the waste hierarchy and identify the environmentally preferable option;
- **Chapter 4 (Using Life Cycle Thinking and Assessment to Support Environmentally Sound Decision-Making)** gives guidance to assess whether initiating a new LCA is necessary to support waste management decisions or whether LCT-based straightforward criteria could suffice;
- **Chapter 5 (Beyond Environmental Aspects – Towards a Sustainability Assessment)** provides an overview of the methods to complement the environmental assessment with cost analysis and social/societal issues.
- **Chapter 6 (Life Cycle Assessment Step-by-Step)** provides key methodological aspects involved in conducting a full Life Cycle Assessment (LCA);
- **Chapter 7 (Technical Guidelines on Waste-Type Specific)** gives practical guidance for developing other guidance documents focused on specific waste streams;
- **Chapter 8 (How to Get Started with LCA on Waste Management)** provides guidance on how to identify the relevant decision-context and on the key data and information needed to conduct an LCA;
- **Chapter 9 (Technical Guidelines for Life Cycle Based Modelling of Waste Management Processes)** focuses on each main waste management options (e.g., recycling, incineration, landfilling) and gives practical guidance on how to conduct an LCA that accounts for all relevant technical and modelling-related aspects. Relevant requirements and recommendations are also highlighted;

A number of annexes have also been included. These expand on some crucial aspects introduced in the document (follow the links for a direct access):

- Annex A – Key definitions provides a non-exhaustive list of important definitions in the context of LCT and LCA;
- Annex B – LCA step by step provides useful information on the procedure to conduct full LCAs;
- Annex C – Key LCA concepts, strengths and weaknesses illustrates a number of key aspects in LCA and provides guidance on how to deal with them; the key strengths and weaknesses are also highlighted;
- Annex D – Developing simplified LCA software tools for waste management applications gives guidelines on how to precede when developing simplified software tools for LCA on waste management.

1.4 Who should use this document and why

The main target audiences of this document are experts in the field of environmental assessment of waste management, to support both technical decision and policy making. This includes companies, public authorities, business associations, consultancies and research centres.

It can be used by these experts to provide guidance on how to approach waste management issues with Life Cycle Thinking and Assessment to help identify the environmentally preferable waste management option. This will in turn help to implement the Waste Framework Directive (WFD, 2008/98/EC) in a way that improves the environmental sustainability of waste management strategies and policies. Using this guidance document will also help to develop robust, LCT-based waste specific guidelines and associated supporting tools/applications.

Policy-makers will find in this guidance document relevant information to help them support the development of more sustainable waste policies and strategies.

1.5 Remarks

This document focuses on the environmental aspects of waste management services. While economic, social/societal aspects are mentioned, no detailed guidance on how to include them is provided in this document.

The recommendations given in this document are intended to help model a limited set of typical waste management and treatment activities, focussing on those processes, parameters and impacts that typically matter most. However, the LCA/LCT results and conclusions cannot be generalised and it is the responsibility of the expert to judge whether existing studies and information are relevant and can thus be extrapolated to a new situation not covered in this LCA/LCT study.

Although this guidance document provides some key elements on how to approach waste management issues with LCT and LCA, reading this document only is insufficient background to enable a person to conduct an LCA according to the standards and good practices.

Where available, it is recommended to consult more comprehensive guides on the specific waste management and treatment processes. These should be developed in accordance with International/European standards and recommendations such as ISO 14040/14044[4] and the ILCD Handbook[5].

1.6 Link to other waste guidance documents

This guidance document is one in the set of guidelines listed below, all developed by the Directorate General (DG) Environment[6] and the Joint Research Centre (JRC)[7], tailored to the needs of different target audiences and focusing on specific waste streams:

- "Supporting Environmentally Sound Decision for Bio-Waste Management – A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)";
- "Supporting Environmentally Sound Decision for Construction & Demolition (C&D) Waste Management – A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)";

[4] www.iso.org
[5] http://lct.jrc.ec.europa.eu/assessment/projects
[6] http://ec.europa.eu/environment/index_en.htm
[7] http://ec.europa.eu/dgs/jrc/index.cfm

2 Why Use Life Cycle Thinking and Assessment in Waste Management Decision Support

What is the focus of this chapter?

This chapter provides an introduction to Life Cycle Thinking (LCT) and to several other widely used LCT-based methods. A brief evaluation of the suitability of these methods for waste management applications is also provided. Further details are then given for Life Cycle Assessment (LCA) and its applications.

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and anyone looking for relevant information to use LCT and LCA for waste management applications.

2.1 Introduction to Life Cycle Thinking (LCT)

Until recently, the focus for environmental improvement actions was on the process, i.e. minimising point sources of pollution, discharges to rivers, emissions from chimneys and so on. In business, this has often meant a strategy of reducing environmental impacts that is confined within the factory gates. These strategies have not considered consequences on upstream supply chains, product use or end-of-life. In Government, actions have focused primarily on the country or region governed, and not considered knock-on impacts or benefits that would occur in other geographies.

In both cases, if there is insufficient attention to the full life cycle (production / supply / use / end-of-life), overall environmental degradation and unwise resource use may result. Additional potential consequences are damaged reputations and impaired financial performance for the parties involved.

Life Cycle Thinking (LCT) is a conceptual approach that seeks to identify improvements and to lower the impacts of goods or services (products) at all stages of associated life cycles, from raw material extraction and conversion, product manufacture, through distribution, use and eventual fate at end-of-life.

The concept of Life Cycle Thinking helps to avoid the situation of resolving one problem while creating another. LCT avoids the so-called "*shifting of burdens*", e.g., from one stage in the life cycle to another, from one region to another, from one generation to the next or amongst different types of impacts (Figure 1).

This type of approach demands more from the policy developer or environmental manager, in that he needs to look beyond his own practices and knowledge. However, it also offers the possibility of significant advantages from the knowledge gained – for example through identifying process efficiencies or good management practices.

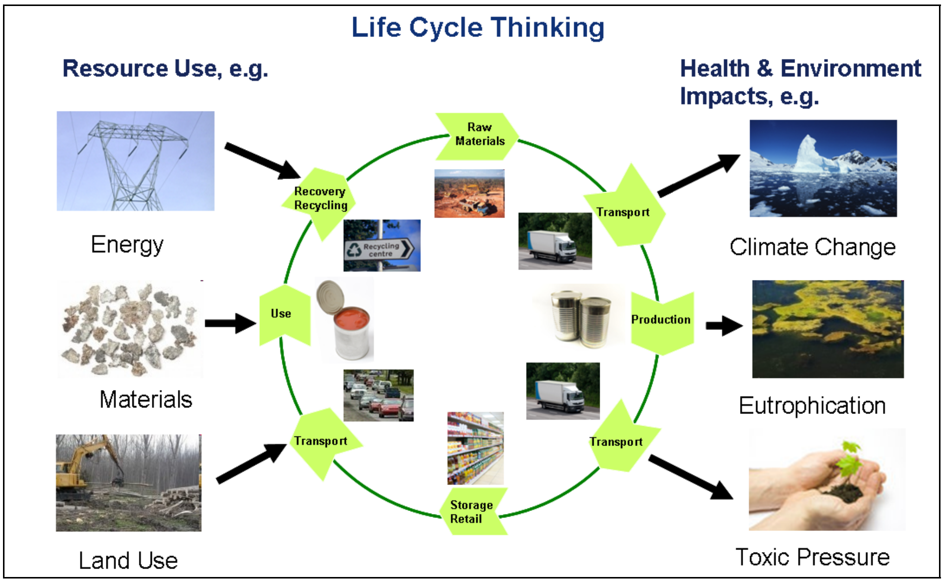

Figure 1: Elements within Life Cycle Thinking (LCT)

2.2 Introduction to Life Cycle Assessment (LCA)

Life Cycle Thinking can be quantified in a structured, comprehensive manner through Life Cycle Assessment (LCA). In LCA, one assesses the emissions, resources consumed and pressures on health and the environment that can be attributed to different good(s) or service(s) taking into account their entire life cycle, from “cradle” to “grave”. LCA is an internationally standardised method (ISO 14040 and 14044)[8] that can provide a rigorous approach for improving decision support in environmental management.

Using LCA, we seek to quantify all the physical exchanges with the environment, whether inputs of natural and energy resources or outputs in the form of emissions to air, water and soil. These inputs and outputs are compiled in a balance sheet, or life cycle “inventory” for a given “system”. After the inventory has been completed, the inputs and outputs are translated into indicators associated with different pressures such as resource depletion, climate change, acidification, or toxicity to plants, animals and people.

LCAs express environmental impacts per "impact category" or environmental problem. All emissions contributing to an environmental problem are converted into a common unit (e.g., kg CO_2-equivalent for climate change, or kg SO_2-eq. for acidification) using conversion factors (known as “characterisation factors”; e.g., for looking at climate change over a 100-year time frame, 1 kg of methane is equivalent to 25 kg CO_2[9]).

Figure 2 shows an example of this process – termed “life cycle impact assessment” (LCIA). Using scientifically-derived characterisation factors, the LCIA step calculates the relative importance of each input and output for the different types of

8 http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54854
9 Based on the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); year 2006

environmental problem. Some of these characterisation factors are very reliable and globally harmonised for some impact categories (such as the IPCC factors used for climate change[10]), but for others (e.g., land use, toxicity) several methods exist and international/European harmonisation is ongoing[11].

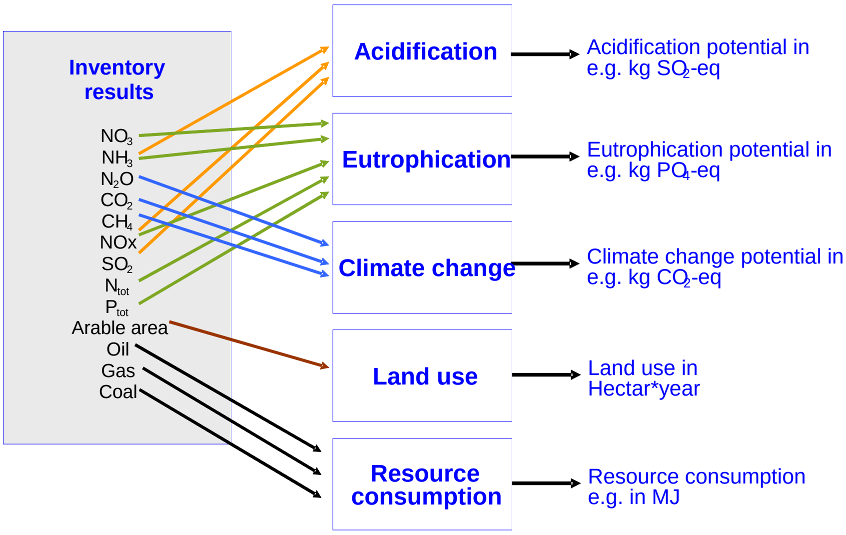

Figure 2: Life Cycle Impact Assessment – translating inputs and outputs into environmental impacts

When LCT/LCA are applied to waste management services, typically the assessments focus on a comparison of different waste management options, not covering the entire life cycle of the products which have become waste. For example, when evaluating different options for bio-waste management, usually the production stages of the food that has become bio-waste, are not considered. Therefore, LCT/LCA applied to waste management services can differ from product LCT/LCA, which accounts for the entire life cycle of a product, in which waste management may play only a minor role. However, if one of the evaluated waste management options includes that materials are given back into the life cycle of a product, a product life cycle perspective has to be taken into account also in LCT/LCA for waste management services. For example, when looking at municipal waste management including recycling, the benefits of saving virgin raw materials in the production stages of products have to be taken into account.

LCA for waste management can be used for a range of applications, from assessing the benefits of avoiding a waste to evaluating different options for management systems. In the context of waste management facilities, an LCA considers the potential direct impacts of the operations on the environment (e.g., stack emissions from an incinerator). It also quantifies the indirect benefits of recovering materials

[10] Intergovernmental Panel on Climate Change (IPCC) 2006, Forth Assessment Report

[11] For more information please refer to http://lct.jrc.ec.europa.eu/

and energy from the waste (e.g., through combined heat and power and ferrous metal recycling).

The results of an LCA can thus help businesses and policy-makers understand the benefits and trade-offs they face when making decisions on waste management options. LCA provides quantitative information which puts potential environmental advantages and disadvantages into perspective.

2.3 LCA standards and recommendations

The International Standards Organisation (ISO) 14000 series addresses environmental issues and includes 14040 and 14044 which relate to Life Cycle Assessment[12]. ISO 14040 and 14044 address not only the technical, but also the organisational aspects of LCA, such as stakeholder involvement and independent critical review of studies. Methodological aspects specify the general principles and requirements for conducting an LCA.

The European Platform on Life Cycle Assessment (EPLCA) and the International Reference Life Cycle Data System (ILCD)[13] promote the availability, exchange and use of coherent and quality-assured life cycle data, methods and assessments for reliable and robust decision support. The ILCD consists primarily of the ILCD Handbook and the upcoming ILCD Data Network, with the former setting requirements for quality and the latter providing access to life cycle data from a wide range of different LCA database developers.

2.4 Experiences with Life Cycle Thinking and Assessment in the waste policy context

The following, non-exhaustive, examples demonstrate how Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) can be applied to legislation and waste management planning, leading to selection of the most preferable environmental option[14].

These examples also highlight that LCT and LCA results do not necessarily lead to an exclusive solution and that the best solution from an environmental point of view varies among regions, among waste treatment facilities, etc. In fact, the environmental appropriateness of one waste management option over another is highly dependent on local conditions (waste characteristics, waste treatment facility performance, location of waste treatment and recycling facilities, etc.).

[12] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54854
[13] http://lct.jrc.ec.europa.eu/
[14] For more examples, please refer to the guide "Supporting environmentally sound decision in waste management – a guide to LCT and LCA in waste management for waste policy-makers and business," developed by the Joint Research Centre (JRC)

2.4.1 England

The 2007 Waste Strategy for England sets general priorities for enhancing recycling and recovery activities and for landfill diversion explicitly based on results of various LCAs: “Recent studies have considered the relative potential benefits for climate change of the recovery of different materials using a life cycle approach[15,16] (etc.)”.

This example shows how LCA can be directly used to influence the waste strategy and planning towards an environmental most preferable direction on national level.

2.4.2 Denmark

In 2005, following new statutory requirements on waste collection, the city of Copenhagen (500,000 inhabitants) needed to look into new options for managing drinks packaging waste, in particular for metals and plastics.

To help with decision-making, a Life Cycle Assessment was carried out to complement an economic evaluation[17]. The latter was conducted through a Cost-Benefit Analysis (CBA). The overall purpose was to verify whether the existing collection and treatment strategy could be replaced by a more efficient one, both from an environmental and economical perspective. The environmental evaluation took into account impacts such as climate change and acidification, measured in tonnes of CO_2-equivalent and SO_2-equivalent, respectively.

Four alternative scenarios were studied and compared to the existing strategy (baseline scenario), which involved collection with other types of household waste, followed by incineration:

- Baseline scenario: collection together with residual waste (followed by incineration);
- Alternative 1: collection for recycling at existing glass bottle banks;
- Alternative 2: street collection for recycling;
- Alternative 3: centralised collection at recycling centres;
- Alternative 4: separate collection in containers placed next to the existing glass bottle banks.

The assessment concluded that street collection (Alternative 2) is preferable from a purely environmental perspective (230 tonnes/year of CO_2-equivalent and 0.6

[15] Carbon Balances and Energy Impacts of the Management of UK Wastes, report by ERM (with Golder Associates) for Defra, Final Report, March 2007, http://www.defra.gov.uk/science/project_data/DocumentLibrary/WR0602/WR0602_4750_FRP.pdf

[16] Environmental Benefits of Recycling: An international review of life cycle comparisons for key materials in the UK recycling sector, WRAP, May 2006, http://www.wrap.org.uk/applications/publications. This report has been updated in 2010: http://www.wrap.org.uk/downloads/Environmental_benefits_of_recycling_2010_update.0429d40c.8816.pdf

[17] Alejandro Villanueva, Karen B. Kristensen and Nanja Hedal (2006). In Danish Topic Centre on Waste and Resources (Ed.): A quick guide to LCA and CBA in waste management. Other environmental impacts, e.g., acidification, were also evaluated in the report for Copenhagen but are left out here for illustrative purposes.

tonnes/year SO_2-equivalent saved compared to the baseline scenario). However, this scenario was identified as the most expensive collection scheme in the economic evaluation. Collection at existing bottle banks (Alternative 1) proved to be the scenario both with the lowest climate change impacts (110 tonnes/year of CO_2-equivalent and 0.4 tonnes/year of SO_2-equivalent saved compared to the baseline scenario) for the lowest financial cost. This has become the new management strategy for used metal and plastic drinks packaging in Copenhagen.

This example demonstrates that life cycle approaches can also be applied to a well defined situation at city level and illustrates how LCA can be used to complement a purely economic analysis. It can help find solutions that are better for the environment while also considering financial constraints.

3 Complementing the Waste Hierarchy with a Life Cycle Thinking Approach

What is the focus of this chapter?

This chapter moves along the steps of the waste hierarchy as defined by the Waste Framework Directive (prevention, preparing waste for re-use, recycling, other recovery and disposal) and explores how Life Cycle Thinking (LCT) can be used to complement the waste hierarchy in order to identify the environmentally preferable option.

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and anyone looking for relevant information to use LCT and LCA for waste management applications.

3.1 Overview

The waste hierarchy (Figure 3) establishes a legally binding framework for waste management projects and strategies to help reduce resource consumption and environmental impacts. However, the waste hierarchy serves as a general principle and there can be several options at each level.

Article 4(1) of the Waste Framework Directive (WFD – 2008/98/EC) confirms that the waste hierarchy as a legally binding priority order for waste management but, at the same time, it is open to potential deviations from the hierarchy (Article 4(2)). However, in order to make sure that the best solution for the environment is identified, the WFD requires that any deviation is justified by life cycle thinking:

Waste Framework Directive (Directive 2008/98/EC)

Article 4(1) – "The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: prevention, preparing for re-use, recycling, other recovery, e.g. energy recovery, and disposal".

Article 4(2) – "When applying the waste hierarchy […], Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste[…]".

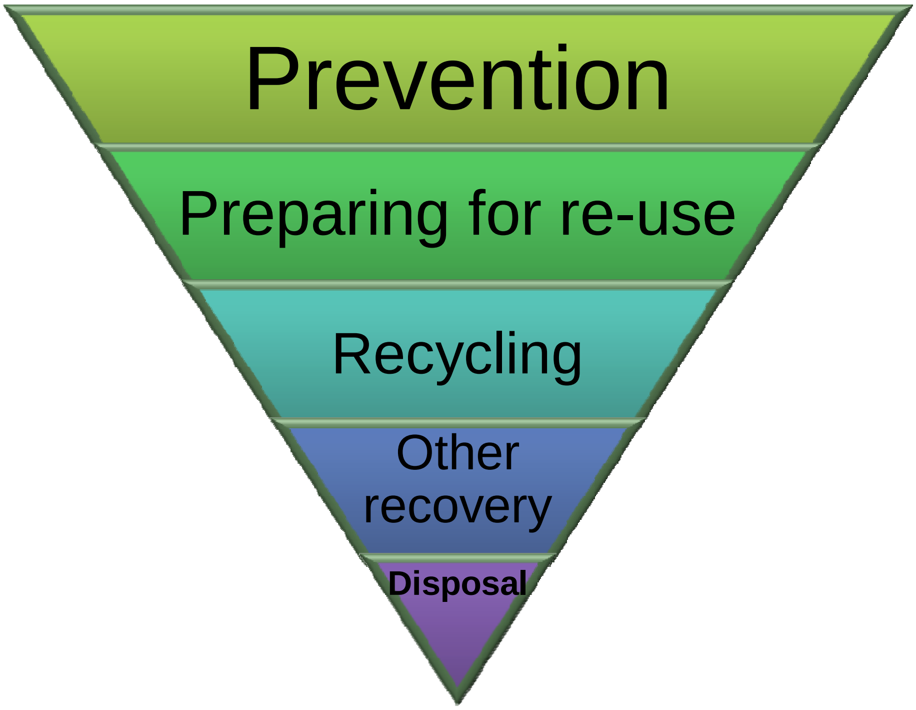

Figure 3: Waste management hierarchy

Life Cycle Thinking (LCT) can be used to complement the waste hierarchy, helping to assess the benefits and trade-offs associated with the different options[18]. In practice, this can be accomplished by transposing LCT into a quantitative methodological framework, such as provided by Life Cycle Assessment (LCA).

LCT and LCA can also be used to help further cross-compare different options at a particular level in the hierarchy (e.g., alternative ways of recycling a certain waste stream). In fact, these will have different consequences, which can be disclosed by LCT and LCA.

The following sections move along the waste hierarchy steps (prevention, re-use, recycling, other recovery, and disposal) and clarify how LCT and LCA can be used to complement the hierarchy principle and support decisions towards identifying the (environmentally) preferable options.

3.2 Waste Prevention

Prevention means reducing, or avoiding generation of waste. This is frequently the best possible solution, as resources are not lost and the negative environmental impacts associated with waste management do not occur. Prevention (as defined in the Waste Framework Directive) also refers to measures taken to reduce the

[18] More information on how to complement the waste hierarchy with an LCT-based approach is provided by the guide "Supporting environmentally sound decision in waste management – a guide to LCT and LCA in waste management for waste policy-makers and business" developed by the Joint Research Centre (JRC)

adverse impacts of generated waste on the environment and on human health. This can, for example, be achieved through minimising the content of harmful substances in materials and products.

There are a number of ways of preventing waste:

- Design a product more efficiently so it requires less material;
- Changing buying behaviour;
- Reduce the amount of packaging (see example in the box below on reduction of steel-can packaging);
- Optimise the manufacturing process so that less material is used in the overall extraction/production process. This can reduce the total amount of materials needed to make a product as well as the total amount of waste generated over the entire life cycle;
- Substitute a resource for another with greater environmental benefits – for example substituting a hazardous material with a non-hazardous one;
- Re-use of a product/good (i.e. without preparation operations e.g., no washing or pre-processing).

The benefits are obvious and can be supported by LCT/LCA when waste prevention does not adversely influence any other aspects of the product’s life cycle.

Reducing the weight of a bottle, for example, has clear benefits as fewer materials are used to produce the bottle and transport fuel costs are lower. However, there can be unexpected side-effects. If the weight of the bottle is reduced too much, its strength may also be reduced. The risk of losing more product is higher, with a bigger impact on the environment than the one represented by the reduction of packaging. Also, the bottle may no longer be strong enough to carry the weight of other bottles stacked above it on a pallet during transport and heavier cardboard boxes could be necessary to help support the weight. The benefits of making the bottle lighter may be offset by the increased use and weight of the cardboard.

This example demonstrates that even straightforward-looking decisions may have more complex implications if the entire system is taken into account in a comprehensive LCT approach. A focus on only one aspect in the life cycle, here the primary packaging (bottle), does not necessarily lead to the best result if all aspects are taken into account holistically (e.g., also the transport phase).

Frequently, the benefits of re-use are straightforward, as re-use avoids the need for the manufacture of a new product. A simple example is the direct re-use of containers, bricks or other materials on site.

However, preventing waste generation through re-use can also mean:

- A separate collection and return system is required if the product is not re-used by the same organisation;

- Need for pre-processing e.g., a washing or reconditioning stage is needed – for example following salvage of building components before demolition;
- More transport emissions occur – if the re-usable product is heavier or has a larger volume than the disposable one, or if the re-conditioning infrastructure is limited and the re-usable product needs to be transported on longer distances;
- Compared to new and more efficient products, higher energy consumption may occur during the re-usable product use phase; this is commonly the case for old electrical equipment which consumes more energy compared to modern equipment.

Example: Optimisation of steel-can packaging

Coffee products arrive to the shelves of grocery shops in packaging of different materials, sizes and weights. What are the environmental consequences?

An LCA study was carried out in the US to compare a number of different coffee packaging systems[19]. The comparison criterion was the emission of greenhouse gases associated with the different packaging systems. The functional unit was set to approximately 3 tonnes of coffee.

As an extract from this study, two alternative steel-can packaging were compared, differing only in the coffee volume capacity:

- Alternative 1: small steel-can. The overall weight of packaging per functional unit is equal to about 850 kg. The greenhouse gas emission associated amounts to about 2,000 kg CO_2-eq.
- Alternative 2: big steel-can. The overall weight of packaging per functional unit is equal to about 610 kg. The greenhouse gas emission associated amounts to about 1,400 kg CO_2-eq.

The use of the big steel-can therefore allows reducing the weight of packaging per unit mass of coffee product. This moves towards waste prevention. Overall, a reduction of about 30% of the overall weight per functional unit (850 to 610 g) results in comparable reduction of 30% of the greenhouse gas emissions associated.

This confirms that if waste prevention can be achieved by using less material – without negatively impacting other areas – it will be highly beneficial and should be promoted. The results of this study are being considered for promoting the use of more environmentally sustainable alternatives for packaging of coffee products.

Example: Should cars be made of lighter or more recyclable materials?[20]

[19] Oregon Department of Environmental Quality, *Oregon Strategy for Greenhouse Gas Reductions* - http://www.deq.state.or.us/wmc/packaging/cs/csnormthompson.pdf

[20] Notice that this example goes beyond waste prevention (through using lighter materials), as recyclability aspects are also involved and influence the overall environmental performance.

Cars manufacturing requires a wide variety of materials. Steel has traditionally been used, but it is partly being replaced by plastics and composite materials. Steel can be heavier than the plastics or composites with the same function. This adds weight to the car, which in turn increases the fuel needed to operate the car throughout the use phase. However, steel parts are easily recycled at the end of the vehicle"s life, while often composites are not.

For a specific case, an environmental impact analysis[21] showed that only if a car is driven more than approximately 132,000 km there is a net benefit gained by using the lighter but less recyclable materials. In other studies and for other car components it was found that light weight construction pays off already after 50.000 km driving or only after > 200.000 km driving distance. In this example there is a trade-off between two environmental benefits. One is the lower fuel consumption due to the use of lighter materials and the other is the energy savings due to recycling. Note that any benefit will also depend on other factors, e.g. the replaced parts and the car type.

This example illustrates that it is important to consider a number of aspects of a product along its entire life cycle, including its weight and recyclability. Reducing weight is typically seen as a way of limiting the adverse environmental impacts of a product. However, this needs to be balanced against the recyclability of the product and its components. The example further suggests that if plastic components were more easily recyclable, benefits for the environment could be greater.

Key LCT Concepts

You can use LCT to guide you in making decisions between waste prevention options and to demonstrate the benefits of waste reduction measures on site, in contract specifications, or in policy choices. LCT is also useful for highlighting where waste prevention measures could pose a risk of actually increasing environmental impacts, rather than reducing them. For example, if taken too far, reduced packaging can result in the packaged product being damaged or lost more frequently and so more materials would be needed to deliver the same amount of packaged products.

There are some key concepts to consider when using LCT to assess waste prevention measures. Of particular importance is the choice of an appropriate **"system boundary"** (the system boundary identifies which processes are accounted for in the assessment and which are not) and what to include in the assessment. This is discussed further in Annex C.

3.3 Preparing for re-use

"Preparing for re-use should not be confused with "re-use". The latter, as clarified in the previous sub-chapter, is a form of waste prevention, thus ranks higher in the waste hierarchy. Under the WFD, the definition of "preparing for re-use" is[22]: "*checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing.*" The key difference between "re-use" and

[21] Duflou JR, et al. Environmental impact analysis of composite use in car manufacturing. CIRP Annals - Manufacturing Technology (2009).
[22] Waste Framework Directive (2208/98/EC), Art. 3(16).

"preparing for re-use" is that in the former case the material or object has not become a waste, whereas in the latter it has.

3.4 Recycling

"Recycling" means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

As the original, or "primary", production of materials can require significant amounts of energy and raw materials, recycling into "secondary" materials can be environmentally very beneficial[23]. For example, separation of metals from Construction and Demolition (C&D) waste and recycling into other metal products has been shown to result in significant environmental savings. There are also considerable financial benefits which already drive the recycling of many materials.

However, various factors can significantly influence the environmental comparison of recycling and alternative management options (e.g., energy recovery and disposal). These include:

- The quality of the secondary products and the level of hazardous substances in the secondary product;
- The product(s) that the recycled material will replace;
- The recycling efficiency (how much product is lost in the process);
- The energy intensity of the recycling process;
- The distance to the reprocessing plant and the type of transport used.

Example: Is recycling of paper and cardboard always the best environmental option?

The earlier mentioned study from the Waste & Resources Action Program (WRAP) "Environmental benefits of recycling – update 2010"[24] also included paper and cardboard waste among the waste streams considered.

In most cases, it was found that recycling delivers the most environmentally-sound performance, as it typically offers more environmental benefits (e.g. avoided emissions) and lower impacts than other options. In any case, this review also highlights where deviations from the waste hierarchy may lead to better solution from an environmental perspective.

[23] See for instance the study "WRAP (2010) *Environmental Benefits of Recycling – 2010 Update"*. WRAP, Banbury, UK.

[24] Michaud, J.C., Farrant, L., Jan, O., Kjaer, B. & Bakas, I. Waste & Resources Action Program – WRAP (2006): *Environmental benefits of recycling – 2010 update*. (http://www.wrap.org.uk/downloads/Environmental_benefits_of_recycling_2010_update.3ee11cfb.8816.pdf)

With respect to paper and cardboard waste, it was concluded that recycling offers a better overall environmental performance compared to landfilling. On the other hand, the environmental preference between recycling and incineration with energy recovery is harder to establish, especially with regards to impact categories such as resource depletion, climate change, eutrophication, ecotoxicity and human toxicity. It was also found that the single most important parameter influencing the environmental preference between recycling and incineration of paper and cardboard waste is the energy mix that is substituted by the energy produced by the incineration option.

This example shows that, while landfilling of paper and cardboard waste environmentally does not compare with recycling, the environmental preference between recycling and incineration with energy recovery may change. An LCA can, in this case, help establish the preferable environmental option and identify the extent to which the various parameters involved (e.g. recycling rate, energy recovery efficiency, energy mix) influence the overall performance.

Key LCT Concepts

LCA can be used to guide you in making decisions between recycling options.

Important concepts to note when assessing the relative impacts and benefits of recycling schemes include "**closed loop**" and "**open loop**" recycling, **recyclability**, **down-cycling** and product "**substitution**". See Chapter 9.5 for more information.

3.5 Other Recovery

An alternative to recovering the material value from a waste stream (i.e., recycling) is to recover the energy inherent within the waste material(s). This can lead to significant environmental benefits, particularly for materials with a high calorific content. For example, estimates of the savings in greenhouse gas emissions of recovering energy from waste wood range from 0.5 to 3 tonnes CO_2-equivalents per tonne of material incinerated, in comparison with landfilling the same quantity[25].

However, evaluation of the benefits and impacts of energy recovery is complex because:

- Energy recovery is possible only once and it is an irreversible step. Potentially, it can prevent materials from being recycled (although countries with the highest recycling rates are typically also those with the highest incineration rate) and products from being re-used;
- The energy recovery efficiency can vary significantly;
- Various parameters can significantly influence the scale of impacts and benefits associated with energy recovery and affect the environmental comparison between this management route and other levels of the waste hierarchy (e.g., recycling and disposal). For example, the type of waste combusted, its **calorific content**, the **amount of energy** captured and the

[25] WRAP (2007) *International Review of Life Cycle Assessments.* WRAP, Banbury, UK

type of energy it replaces are key considerations in assessing environmental impacts/benefits. Chapter 9.9 and Annex C explore these aspects further.

Key LCT Concepts

You can use LCT to guide you in making decisions between energy recovery operations, other recovery operations (such as co-processing and co-incineration) and other management options. LCT is also useful for highlighting where waste recovery could pose a risk of actually increasing environmental impacts, rather than reducing them.

There are some key concepts to consider when using LCA to assess waste recovery. Of particular importance is the choice of the "system boundary" and, for energy recovery, of the energy mix that is substituted by the energy produced from the waste. This is discussed further in Chapter 9.9.2 and Annex C.

3.6 Disposal

Although at the bottom of the waste hierarchy, there are occasions in which waste disposal at landfills is unavoidable. For some waste types, landfilling causes only minor environmental impacts (e.g. some C&D waste) and there may also be occasions where this corresponds to the best environmental solution. Consider the case of inert materials with low technical performance. To be recycled as aggregate, they may need to undergo further re-processing and transportation to a distant point of use. The impacts of doing so may be greater than both the "avoided burdens" of producing primary aggregates and disposing of the inert waste material in a landfill.

However, disposal of waste to landfills can also mean:

- Significant emissions of methane and greenhouse gases when biodegradable waste is landfilled;
- Contamination of surface water bodies and groundwater due to emission of leachate;
- Fire/explosions risks, noise, litter and dust (please note that these aspects are typically not considered in LCA);
- Occupation of vast land areas that could otherwise be used;
- Negative impact on future generations by diverting potential raw materials and dumping waste;
- Preventing the move towards a recycling society.

Key LCT Concepts

You can use LCT to guide you in making decisions between waste disposal (e.g., landfilling) and other management options.

There are some key concepts to consider when using LCT to assess waste disposal. Of particular importance is the choice of "system boundary" and of the time horizon of the assessment. This is discussed further in Chapter 9.12.2.

4 Using Life Cycle Thinking and Assessment to Support Environmentally Sound Decision-Making

What is the focus of this chapter?

This chapter illustrates how to approach waste management issues with Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA). Guidance is provided on how to assess whether initiating a new LCA is necessary for this purpose, or when LCT-based straightforward criteria may be sufficient. On the other hand, when conducting an LCA is needed, reference shall be made to Chapters 6 to 9.

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and civil servants supporting public decision makers, who need to understand the fundamentals of LCA process.

4.1 Overview

A simplified decision-tree is here provided to give guidance on how to approach and address waste management issue with LCT and LCA.

As the decision-tree shows, the starting point is the recognition of the fact that waste management decisions are to be taken. These should then be formulated in a way that provides a clear description of the alternative waste management options available, especially with focus on their potential environmental consequences.

It can then be evaluated whether applying waste hierarchy would allow to clearly identify the preferable environmental option, or whether evidence from previous work exist that would be sufficient to support decision-making. If this is not the case, straightforward, LCT-based criteria may be derived and used. When straightforward criteria do not apply, then conducting a new LCA may become needed to identify the preferable waste management option. These aspects are presented on the next sub-chapters.

As the decision-tree shows, not only the environmental aspects should be considered to provide comprehensive support to decision-making and policy making. The LCA results should, therefore, be complemented with information gained from analyses of the social and economical implications (Chapter 5 expands on this).

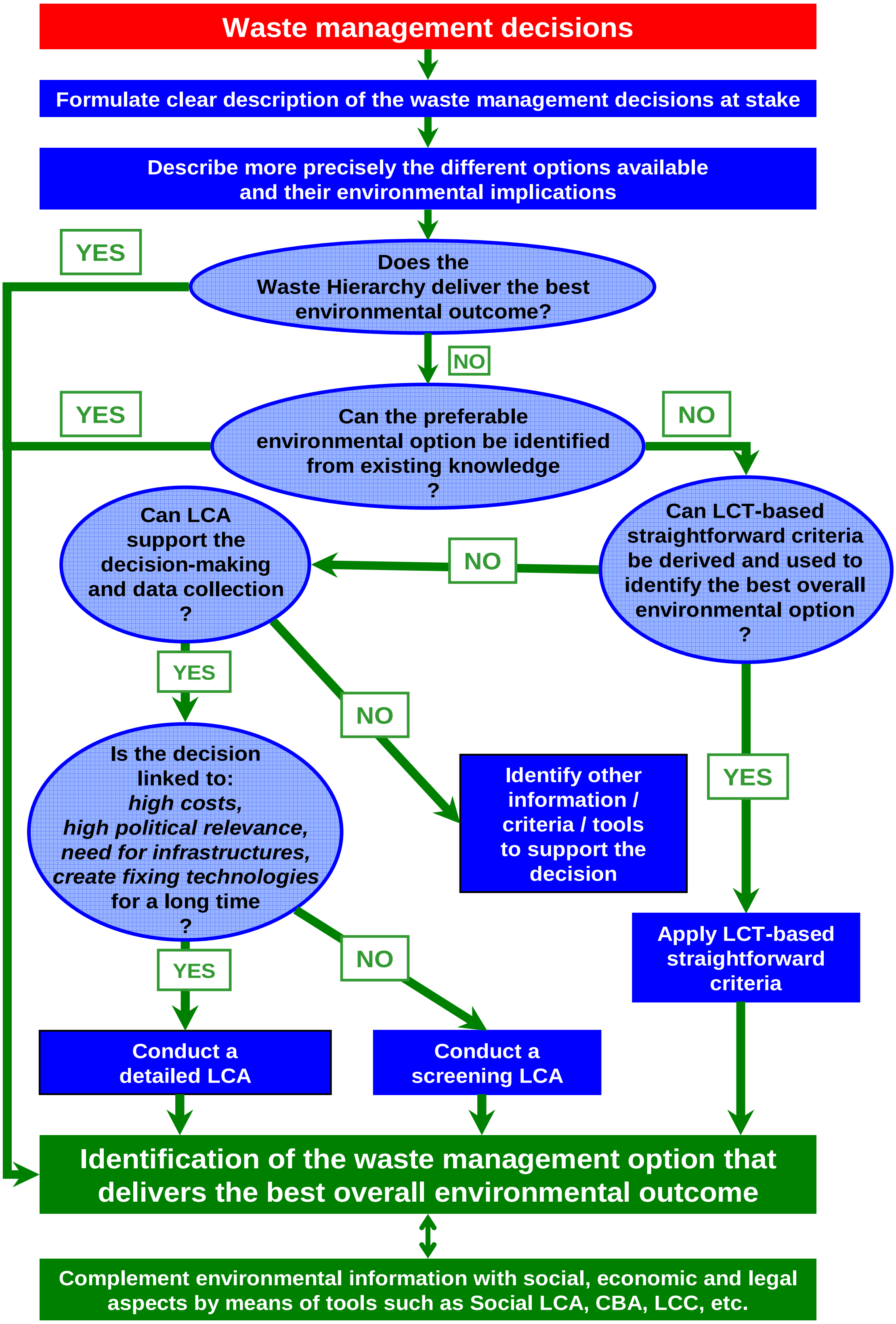

Figure 4: How to approach waste management issues and decision with a LCT-based approach

4.2 Supporting decision-making with existing knowledge

There may be instances where it is important to establish whether existing knowledge meets a sufficient level of quality and consistency, e.g., to determine when LCA results are eligible for transfer to other similar cases. This is for instance the case when evidence from existing LCAs would be sufficient to support decision-making in the context under evaluation. As an example, with respect to the management of a given waste stream, if there was LCA-based evidence that option X performs better than option Y (from an environmental view point) in a given context, would this conclusion be applicable to a different waste management context?

In order to evaluate quality and consistency of an existing LCA, reference shall be made to the ILCD Handbook guide "Review scope, methods and documentation for Life Cycle Assessment (LCA)[26]". The guide highlights that quality and consistency can be verified by checking if the LCA has undergone a "critical review", the type of review, and what this has concluded. A critical review assesses whether an LCA or related data has met pre-defined requirements. This can help avoid errors and help ensure that all options or method requirements have been appropriately considered. The guide includes:

- Analysis of the documentation produced during the LCA work;
- Comparison with data and information on the same issue from other independent sources;
- Comparison with applicable legal limits;
- Analysis of data sources used;
- Analysis of energy and mass balances;
- Analysis of context-specific relevant chemical balances;
- Verification of the assumptions (e.g., on the energy mix);
- Verification of other key calculations.

The principle requirements for reviews are addressed in the ISO 14040 series. This addresses not only the technical, but also the organisational aspects of LCA, such as stakeholder involvement and independent critical review of studies. Methodological aspects are set out in ISO 14040:2006[27] and ISO 14044:2006[28]. These specify the general principles and requirements for conducting an LCA. The standards are supported by Technical Reports that provide guidance on dealing with some of the more difficult methodological issues in LCA. However, while other LCA-

[26] At the time of development of this guidance document, the ILCD Handbook guide "Review scope, methods and documentation for Life Cycle Assessment (LCA) was still being finalized and it will become publicly available at http://lct.jrc.ec.europa.eu/publications during 2011.
[27] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=37456
[28] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=38498

based standards define some review requirements in more detail, none of them provides information on how to conduct the reviews, or the required qualifications of reviewers. This gap is filled by the referenced ILCD Handbook[29].

4.3 Supporting decision-making with Life Cycle Thinking

Conducting an LCA to support decision-making in waste management may not always be needed, or even helpful. There may be instances in which evidence from previous work is enough to support decision-making or when LCT-based, straightforward criteria are sufficient to unambiguously identify the environmentally preferable waste management option. What approach can then be taken to establish whether or not an LCA is needed?

4.3.1 Is an LCA needed? - Decision points in a policy context

The following decision tree (Figure 5) provides procedural guidance to assess whether an LCA is needed to address a given waste management issue. This is here approached from a policy-making perspective.

As a starting point, one should scrutinise existing available studies on comparable waste management issues (e.g., issues of similar nature, similar geographical and socio-economic background conditions, etc.)[30]. Evidence may in fact exist that the issue can be approached, if not solved, in a similar manner. To ensure quality, these studies should, as a minimum, be ISO compliant and ILCD compliant, which includes a qualified and independent external review.

When robust studies on comparable issues do not exist, or are unavailable, one should consider other aspects before a full LCA is undertaken (e.g., consider using tools/criteria that have been developed for such purposes, focusing on the key issues as identified from LCAs and other information). With respect to the waste management issue to be addressed, these aspects include:

- The actual potential for environmental trade-offs or burden-shifting resulting from the decision that needs to be taken;
- The extent to which the decision may affect multiple stakeholders and interested parties;
- The extent to which the decision may affect the market or have other consequences, e.g., technological lock-in;
- The extent to which the waste stream(s) involved in the assessment may pose threats to the environment or human health.

[29] Available online at http://lct.jrc.ec.europa.eu/publications
[30] Ideally, to avoid misleading extrapolation of results, the studies should provide the same service(s)/function(s), i.e., have the same “functional unit” (see chapter 5.3)

It is noted that when ISO 14040 and 14044 and ILCD-compliant waste management software tools (that work with a limited set of key parameters and waste characteristics) become available, it may be substantially more cost-efficient to use these tools directly for decision support, instead of searching available literature and analyzing the results of encountered studies.

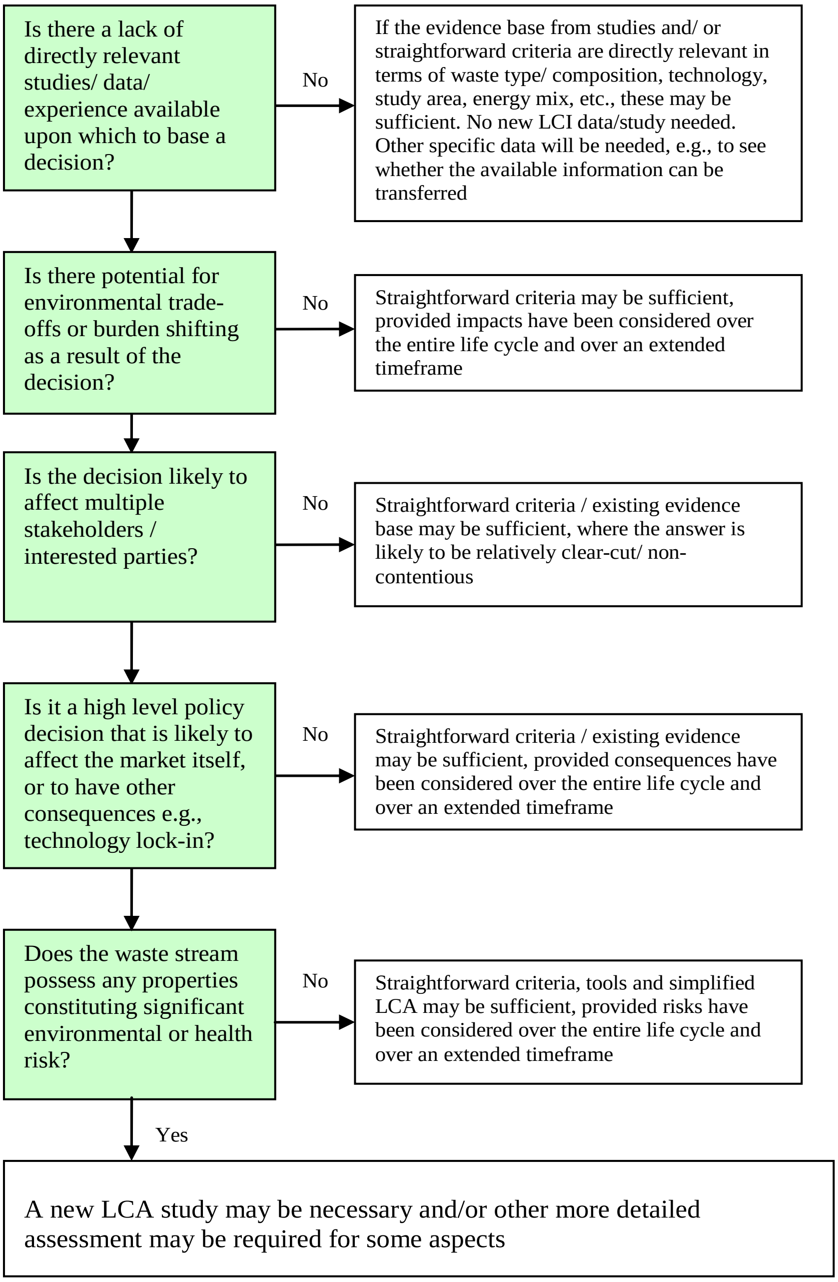

Figure 5: Is an LCA and/or a more detailed assessment needed? Decision points in a policy context

4.3.2 Is an LCA needed? - Other key decision points

In order to judge whether an LCA is needed to address a given waste management issue, in addition to the policy-making perspective, one should also consider a number of other aspects related to the goal and scope of the study. These are presented in the following table (Table 1).

Table 1: Is an LCA and/or a more detailed assessment needed? Other key decision points

Question	Straightforward criteria or existing evidence may be enough if…	An LCA study may be required if…
Is the budget available sufficient?	…the available budget allows financing an LCA expert to check whether existing LCA results may be extrapolated	…the available budget is sufficient to cover all the expenses to undertake a new LCA
Who is the study for?	…the results of the assessment are to be used for internal purposes only, for example, to prioritize actions to reduce environmental pressures but without the need for high levels of quality assurance.	…external communication is required, for example, when reporting to authorities, environmental groups and with other partners.
What information do you have?	…you have a good idea of the types of wastes that you are handling, if the separated materials are of good quality and whether there is a known market.	…you are unsure of the composition of your wastes (additional estimates of composition may be needed), if the quality of separated materials is variable or their market is unknown (some sense-checking of messages may be required).
What options are available?	…you are dealing with materials that have established and optimized reprocessing routes, such as metals.	…you are dealing with materials for which there may be different reprocessing or recovery technologies in different local situations, such as wood or plastics. The potential for future development of technologies for these materials might also be useful to consider.

4.3.3 Deriving LCT-based straightforward criteria

When an LCA is not needed, the environmentally preferable waste management option can be identified using practical life cycle-based approaches such as straightforward criteria, and simplified software tools (Chapter 4.3.4 and Annex D). In order to accommodate robust, science-based decisions, the results of these straightforward approaches must be consistent with findings of detailed LCAs and other information relevant to the decision context. This sub-chapter expands on how to derive straightforward criteria, while Annex D gives guidance on how to develop simplified software tools.

The "waste hierarchy" (i.e., prevention, preparing for re-use, recycling, other recovery, disposal), the legally binding priority order for waste management established in Article 4(1) of the Waste Framework Directive (2008/98/EC), can be seen as a first point of reference for such straightforward criteria. However, often more detailed and specific evaluations are necessary, also to be able to establish the environmental preference amongst specific options belonging to the same level of the waste hierarchy, e.g., amongst different recycling options for a given waste stream. While belonging to the same level of the waste hierarchy, they can differ greatly in their environmental performance. In some cases, these detailed and specific evaluations are also necessary to establish the environmental preference among options belonging to different steps of the waste hierarchy.

Developing and using straightforward criteria and simplified tools can be seen as a valuable and effective step in between applying the waste hierarchy and conducting detailed LCAs. Straightforward criteria and tools often can be derived from the available experience and knowledge gained from previous successful applications of LCT and LCA in comparable waste management contexts.

To ensure factual and robust results, the development and the use of straightforward criteria and tools must adhere to some principles and requirements. Otherwise, there is a risk that relevant environmental aspects are either completely overlooked or under/overestimated leading to wrong decisions. Conformity with ISO 14040 and 14044 as well as compliance with the ILCD Handbook[31] would ensure this.

When used to encourage the options that deliver the best overall environmental outcome, straightforward criteria should be broadly based on scientifically sound methodologies and quality data that are accepted by relevant stakeholders. They need to lead to sufficiently thorough and comprehensive results for the intended application. For example, these straightforward criteria can be criteria derived from detailed LCAs based on a consistent framework methodology that also includes quality-assurance mechanisms, like the International Reference Life Cycle Data System (ILCD)[32].

Moreover, it is paramount that all relevant waste management options are identified and evaluated in a systematic and consistent way to ensure a fair comparison. This includes:

- All relevant environmental impacts are taken into account;
- Key material and energy flows, and key emissions into air, water and soil are identified;
- Key technical parameters of waste management options are identified, e.g., separate collection efficiency, efficiency of waste recycling technologies, efficiency of material recovery technologies, energy recovery efficiency, transport distances, and others;
- Key parameters of the waste composition are identified, e.g., in terms of elemental composition, heavy metals, energy content, water content;
- The assumptions made are transparently documented (e.g., rate of decay of organic materials in landfill, efficiency of energy recovery);

[31] http://lct.jrc.ec.europa.eu/assessment/projects
[32] http://lct.jrc.ec.europa.eu/assessment/data

- Data gathering and evaluation efforts are focused on data and parameters identified as key;
- Uncertainties of the results are evaluated, taking into account the relevance of the omission of information that is identified to be not key.

It must be noted that the above aspects may differ on a case-by-case basis, e.g., according to the waste type and different waste management options.

4.3.4 Simplified software tools

In addition to straightforward criteria, LCT-based software tools for the environmental assessment of waste management systems and strategies may be used. These need to be based on quality-assured data and might take into account straightforward criteria.

LCT-based software tools should allow users to carry out an LCA in a quick and simple manner. If intended for non-LCA experts they must focus on the most relevant technical and management parameters only, not requiring LCA expertise, and helping the user up to results interpretation, identifying its limits.

Annex D provides more detailed guidance on how to develop and use LCT-based simplified software tools for waste management applications.

4.4 Conducting a new LCA

When appropriate LCA-based evidence from existing studies is not available (i.e., it does not exist or it cannot be accessed) and straightforward criteria do not apply, then a new LCA is necessary. This section outlines some key aspects that one should observe to launch a new LCA; links are provided to relevant chapters of this guidance that could be useful to continue the study.

When the decisions to be taken have high relevance (e.g. political, social), then a detailed LCA may need to be conducted. A detailed LCA includes considerable primary data collection related to the product’s supply chain, use, and end of life. It is compliant with the principles and requirements of the ISO standards on LCA and can be used fully to support public disclosure of comparisons between options.

Conversely, a screening LCA may be sufficient. In a screening LCA, a simplified approach is taken, generally by limiting data collection, using generic data where appropriate or assessing only one type of environmental impact (e.g. greenhouse gas emissions). The focus can be guided by more comprehensive assessments (otherwise it risks being misleading). This may result in less complete or less precise information. Nonetheless, it can give sufficiently robust outputs that can answer some key questions. The use of “carbon footprint” tools to assess tenders for waste contracts is an example of a streamlined life cycle approach, although considering only one environmental impact category can be misleading.

As a starting point in an LCA project, within the LCA "goal definition" stage, it is crucial to establish and define the LCA goal and identify the pertinent decision-context situations. This is defined in the ILCD Handbook[33] as "decision-context situation". Three decision-context situations are identified:

- Decision context A: micro-level decision support (Chapter 8.1.1 expands on this);
- Decision context B: meso/macro level decision support (Chapter 8.1.2 expands on this);
- Decision context C: accounting (Chapter 8.1.3 expands on this).

[33] http://lct.jrc.ec.europa.eu/assessment/projects#d

5 Beyond Environmental Aspects – Towards a Sustainability Assessment

What is the focus of this chapter?

In order to provide comprehensive and robust support to decision-making, other aspects should be considered in addition to the purely environmental aspects.

This chapter provides an overview of the methods available to complement the environmental assessment with cost analysis and consideration of social/societal issues. Cost and social/societal issues are seen as crucial for supporting decision-making in any sector, including waste management.

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and anyone willing to use LCT and LCA for waste management applications, e.g., to support waste policy making and planning of waste management strategies.

5.1 Overview

Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) can provide crucial information to support the decision-making process. LCA provides a picture of the contributions a product makes to different impact categories accumulated over time and geographic areas. It complements other information but it does not replace all decisions that need to be made. It is important to remember that LCA is only one of many decision-support tools and that the environment is only one of a range of factors that should be taken considered in making sustainable waste management decisions.

It may also be necessary to make value choices dependent on the outcome of assessments of economic and social criteria. Article 4 of the Waste Framework Directive (2008/98/EC) establishes “economic viability” and “economic and social impacts” as decisive criteria for the implementation of the waste hierarchy.

The current trend is to strive toward a full assessment of goods and services within the context of sustainable development (SD). The combination of Life Cycle Thinking (LCT) which includes the so-called three “pillars of sustainable development” (economic, environmental and social), aims at getting such global picture of societal impacts associated with goods and services.

Assessment instruments including cost analysis and social assessment exist or are being developed. Such methods can be used in parallel to (environmental) LCA or combined / integrated into a multi-pillar assessment, as described below. All of these methods can be used to support decisions related to waste management. Social and cost assessments analogous to the environmental LCA can also be conducted to address the full life cycle associated with goods and services.

5.2 Mono-pillar methods

Methods based on the analysis of one pillar of sustainable development are presented here for economic and social aspects. They can be used on their own or in parallel to other methods. In the latter case, coherent system boundaries and methodological approaches should best be used. As for LCA, these methods require checking of data quality and sensitivity analyses. The role of monetisation as a further step in LCA or social analysis is also described.

5.2.1 Life Cycle Costing (LCC)

Life Cycle Costing (LCC) is a structured approach to establish the cost of different options over their entire life cycles. It is defined as the present value of all monetary costs, negative or positive for fulfilling the functional unit. Examples of costs are investment costs, operative costs, decommissioning costs, and sales revenues (a negative cost).

For waste management, it is crucial to take into account not only the direct costs but to consider all costs along the life cycle, e.g., the cost savings to society as a whole if materials can be recycled and do not need to be disposed, or the additional costs for long-term monitoring and aftercare for landfills for biodegradable waste.

Remark: Prices can integrate several steps of the life cycle

For the economic analysis, it appears that prices can reflect in a single value several steps of the life cycle.The price of a product reflects the upward part of the supply chain while the price of a waste material integrates the downward chain of treatment and valorisation.

Example: The price of a PET bottle bale is an estimate of the cost of the recycling operations as well as of the revenue arising from the sales of regenerated PET.

According to the goal of the study, it has to be decided whether the aggregation into the price is appropriate or whether costs arising at each step have to be determined for example in case of optimisation of waste management.

LCC can be used as a tool for analyzing the economic effects of an (environmental) LCA system. In that case, the underlying structured approach is identical to LCA, facilitating coherent system boundaries and modelling as well as use of environmental LCA and economic LCC information. A SETAC Working Group has developed a methodology for environmental Life Cycle Costing defined as: "*An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or End of Life actor) with complementary inclusion* *of externalities that are anticipated to be internalised in the decision-relevant future*"[34].

5.2.2 Social Life Cycle Assessment (SLCA)

Social Life Cycle Assessment (SLCA) is at a young stage of development. Guidelines (code of good practices) were published in 2009 by UNEP-SETAC[35]. An SLCA is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycles encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal. Social and socio-economic aspects assessed in SLCA are those that may directly affect stakeholders positively or negatively during the life cycle of a product. They may be linked to the behaviours of enterprises, to socio-economic processes, or to impacts on social capital.

When considering waste management, collection of primary or detailed data may be required for different steps of the life cycle for environmental and social analyses. For example, consideration of a manual sorting centre can be low from an environmental point of view, while large in terms of employment and job quality because of the labour intensity of this activity.

The following relevant issues could be addressed, as classified according to the target group of the social impacts:

- Impacts on worker: some steps of the life cycle, such as waste collection and sorting, can be labour-intensive, making job quality a significant issue; furthermore, effects in terms of job creation can be interesting to study. Indeed, the sector of waste treatment is in a number of cases organised as a social economy, hence providing jobs that facilitate re-entry on the employment market;
- Impacts on local community: waste treatment sites, such as landfill sites or incineration plants, can be sources of disamenities for the surrounding population or can be poorly accepted because of risk perception. Among the disamenties are those related to the sites (odour, landscape, etc.) and/or to associated waste transport. When using SLCA together with LCA, it has to be stressed that trouble boundaries exist between environment and social aspects regarding such disamenities. It has to be verified that these aspects are indeed taken into account in either the environmental or the social approaches;
- Impacts on society: time and space required by waste management at home may be worth considering in performing the study.

[34] Hunkeler, D., Rebitzer, G., Lichtenvort, K. (Eds.); Lead authors: Ciroth, A.; Hunkeler, D.; Huppes, G.; Lichtenvort, K.; Rebitzer, G.; Rüdenauer, I.; Steen, B. (2008). Environmental Life Cycle Costing. SETACCRC, Pensacola, FL, p 173

[35] UNEP-SETAC: "Guidelines for Social Life Cycle Assessment of Products" 2009

5.2.3 Monetisation

Monetisation is not an instrument for assessment of economic impacts but can be seen as a step in the interpretation and communication of LCA (or SLCA) results.

Through monetisation, weights are attributed according to the monetary values of the associated damages or benefits affecting e.g., humans (through their environment, resources, job quality, etc.) and ecosystems.

The advantages of monetisation are:

- Benefits can be directly compared to costs;
- It allows direct comparison of effects of different natures since they are expressed in a common unit (euro or other currency), and ranked based on the weighting resulting from the monetary values;
- Results of a multi-impact evaluation can be expressed as a single score, allowing direct comparison between several systems. However, care is necessary to highlight any inherent value choices influencing the single scores;
- Monetisation acts as a filter that helps to distinguish negligible impacts that should not be discussed further and significant impacts on which to concentrate further for data refinement and results discussion. In this sense, it helps lower the study uncertainty by improving the relevance of data collection. Monetisation also acts as a filter to distinguish negligible impact categories that should not be discussed further. In this sense it helps lower uncertainty by improving the relevance of impact categories taken into account in the decision-making process.

Disadvantages of monetisation are:

- It is not (yet) standardised;
- It is based on estimates of actual impacts, while modelling from potential impacts (e.g. equivalent SO_2 emission for acidification) to factual impacts (e.g. effect of acid rain on building degradation) may be highly uncertain. The uncertainty about the impact estimates, together with the uncertainty about monetisation of these impacts, must therefore be carefully discussed and reflected in conclusions in order to be considered in the decision-making process.

  Nevertheless, this can provide valuable additional information/insights. As such, monetisation does not add any uncertainty, as this uncertainty is intrinsically present and a lack of knowledge can be worse than limited knowledge. But, CBA can give the impression that results are precise and inclusive, leading decision makers to decisions they would not necessarily take;

- It can have the effect of by-passing decision makers by directly providing costs data that - despite the inherent restrictions and uncertainties - may be abused by decision makers to avoid having to consider all the information available and uncertainties. Results must, therefore, be carefully presented along with assumptions and uncertainties, as in any assessment.

5.3 Multi-pillar methods

Combinations of environmental and economic analyses based on life cycle approaches have already been widely used. These include cost-benefit analysis and cost-efficiency analysis (see Figure 6).

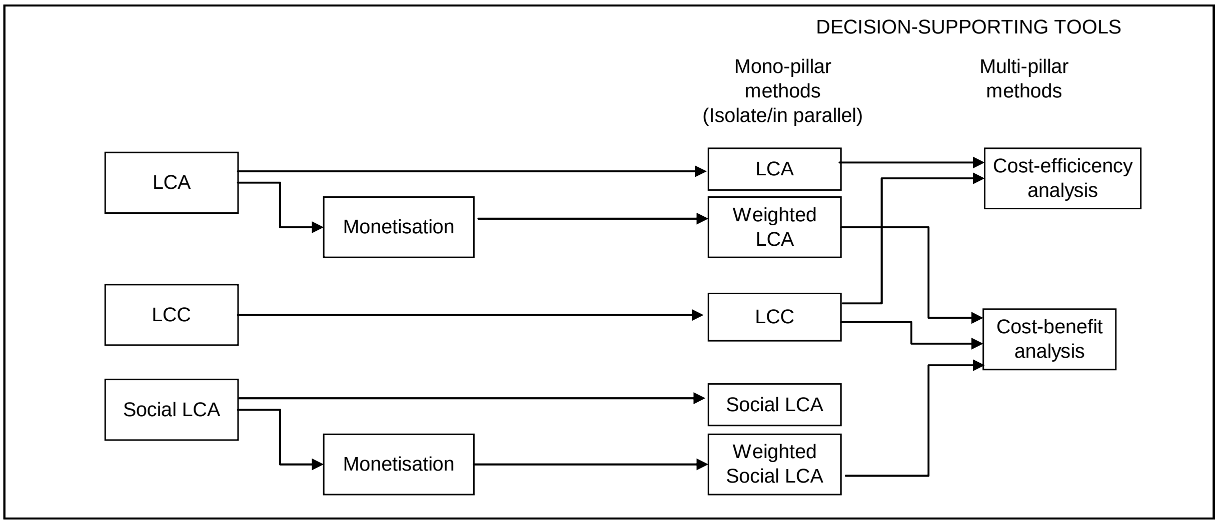

Figure 6: mono-pillar and multi-pillar life cycle methods[36]

5.3.1 Cost-Benefit Analysis (CBA)

In a Cost-Benefit Analysis (CBA), the costs and benefits for the society of a policy, a project, or a product are evaluated. When a project is affected by factors for which the current market prices do not reflect the benefits for the society, a CBA can be a useful tool for shedding light on the benefits for the society to carry out the project or not. Such external factors are namely the costs of the effects on the environment or on the social domain.

The global value for the society (or socio-economic benefit) of a project is calculated as the sum of the net present values of economic costs (in negative) and external benefits, determined within a common analytical framework. Externalities include non-internalised costs (positive or negative) obtained by monetisation of environmental and social impacts. Monetisation of social impacts is however at a much younger stage of development than for the environment. However, studies

[36] Adapted from M. C. Reich: *Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC).* Journal of Cleaner Production 13 (2005) 253–263

converting social and environmental impacts into euro, thus making a full comparison with economic costs possible, have been published.

In practice, the global benefit of a project is calculated. If it results in a numerically positive value, the project is worth being implemented from a societal perspective.

Alternatives can also be compared through CBA for determining the most beneficial (or less detrimental) system. In such a comparison, the study can be simplified by omitting costs or benefits that are common and identical for all the compared systems. The aim of the study is then not to assess whether the global benefit for the society is positive but to compare results obtained for the various systems.

Geographical boundaries can be fixed for example because a decider is only interested in employment in a limited region. Such boundaries can be common to environmental, social and economic analysis. They could also be different in case, for example, environment is a concern at the global scale while social and economic effects are only examined at local scale (municipal, regional, national).

Several CBAs have also been performed as one input to help inform the European Commission, amongst others, on packaging recycling and re-use systems. Since 2007, Nordic guidelines on CBA in waste management are available[37]. These are generally combined with other information in the decision-making process, and typically the underlying information and uncertainties need to be assessed; not just the final monetised result.

5.3.2 Cost-efficiency analysis

Cost-efficiency analysis, or eco-efficiency, can be defined as the ratio of net environmental benefits (measured by LCA) to the difference in costs (obtained through LCC).[38] It reflects the trade-off between the economic and environmental aspects. It is usually analysed for determined environmental targets or objectives.

For example, it can be used to compare the environmental performances of end-of-pipe measures while taking into account their respective cost.

Example[39]

"In commission of OVAM, VITO performed a Life Cycle Assessment (LCA) and an Eco-efficiency analysis on 4 types of drinking cups for use at events. The reason to set up for this study was the introduction of the polylactide (PLA) cup at Flemish events. The objective was to obtain insight in the current environmental impacts and the costs related to existing systems for drinking cups on events in Flanders (Belgium).

[37] *Nordic guideline for cost-benefit analysis in waste management*, Nordic Council of Ministers, Copenhagen, Denmark (2007). Available online at http://www.norden.org/da/publikationer/publikationer/2007-574/at_download/publicationfile

[38] The ratio is often calculated in the sense of maximizing the benefits per euro spent. The inverse ratio can also be calculated for evaluating the cost for reaching a target (for example the cost of abated ton of CO_2).

[39] Department of Waste and materials management OVAM - Flemish Public Waste Agency; http://www.ovam.be/jahia/Jahia/pid/1435?lang=en

In the study, three one-way cups (the PP, the PE-coated cardboard and the PLA-cup) are compared to the reusable PC-cup in both small and large events. In the eco-efficiency analysis, the LCA was related to a Life Cycle Cost analysis to finally assess and compare the eco-efficiency of all the 4 alternatives. Both analyses were, according to the ISO 14040-standards on LCAs, subject of a critical review by a review panel coordinated by TNO.

The LCA resulted in a comparative environmental profile in which nine environmental impact categories were considered. None of the four considered cups show overall superior performance for neither small nor large events.

In the eco-efficiency analysis the 9 environmental impact categories were, on request of the commissioner, elaborated into one environmental indicator which was compared with a cost indicator. The analyses showed that the reusable cup has a significantly more favourable environmental score for small events. For large events no significant differences between the four cups exist. A sensitivity analysis showed that in the near future, taking into account the potential improvements for the PLA-cup system, the PLA-cup might become the best choice.

6 Life Cycle Assessment Step-by-Step

What is the focus this chapter?

This section builds on the ISO 14040 and 14044 standards[40] (on LCA) and on the ILCD Handbook[41] "General guide for Life Cycle Assessment – Detailed guidance." It also explains the key methodological aspects (the five-phase procedure) that are encountered when conducting a full LCA. More details are given in Annex B. Technical guidance on LCA specifically applied to waste management is provided in Chapters 7 to 9.

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and anyone else looking for relevant information to use LCT and LCA for waste management applications.

6.1 Overview

When conducting a comprehensive LCA, first of all an independent review panel is chosen. Then, a five-phase procedure is followed:

- 1st phase: Goal definition (Chapter 6.2)
- 2nd phase: Scope definition (Chapter 6.3);
- 3rd phase: Life Cycle Inventory – LCI (Chapter 6.4);
- 4th phase: Life Cycle Impact Assessment – LCIA (Chapter 6.5);
- 5th phase: Interpretation of results (Chapter 6.6).

These phases often involve iterations (mainly to improve data quality as necessary). Preparation of a draft LCA report follows completion of these five phases. The draft report is then submitted for review to the Review Panel. Preparation of the final LCA report should reflect analyses of reviewer comments and suggested revisions.

The following table (Table 2) provides an overview of the five-phase procedure for conducting LCAs; examples and key elements are provided for each phase. As shown in Table 2, a crucial task in the LCA scope definition is to identify the "**functional unit**", i.e. the service or function the system being investigated delivers to the user. For example, in municipal waste management the functional unit can be collection and treatment of all household waste in a given region and year. All environmental burdens are then expressed relative to this functional unit. For comparing different waste management options, it is crucial that they provide the same function. Otherwise, a fair comparison between systems is not possible (Annex B and Annex C expand on these aspects).

[40] http://www.iso.org/iso/home.html
[41] Available online at http://lct.jrc.ec.europa.eu/publications

LCA is an iterative process. For example, one might need to revise the initial definition of goal and scope based on the findings of the inventory analysis, e.g., refine the system boundary to include a process that was initially disregarded.

Table 2: The five phases of Life Cycle Assessment

Phase	Key Elements	Description
Goal	**Six aspects of the goal definition**	Identify the following: • Intended application(s); • Proposed study methods, important assumptions and impact limitations (e.g., Carbon footprint); • Reasons for conducting the study, and the decision context; • Target audience; • Comparisons to be disclosed to the public; • Commissioner of the study and other influential actors.
	Classify the decision context	Identify the decision context: • Whether the study is interested in the potential consequences of this decision; • The extent of changes - further differentiates the decision-support cases into those that have only small-scale ramifications versus those that have large scale ramifications.
Scope	**Define Function, Functional unit and reference flow**	• Identify the function of the subject product for both qualitative and quantitative aspects; • Identify the reference unit for measurement and analysis.
	Life Cycle Inventory (LCI) modelling framework	• Identify the LCI modelling approach according to the decision context.
	System boundary	• Identify which processes are included and which processes are excluded.
	Preparing the basis for the impact assessment	• Identify relevant impact categories
	Type, quality and sources of required data	• Identify whether data quality is sufficient (in terms of data accuracy, precision / uncertainty and completeness of the inventory; • Check whether all foreground and background data used in a LCI/LCA study are methodologically consistent.
	Comparisons between systems	• Identify whether this study includes comparative assertions; • Identify if the study includes comparisons and whether additional requirements are needed.
	Identifying critical review needs	• Identify proper review type according to target audience and final deliverable.
	Planning reporting	• Identify proper report type according to target audience and final deliverable.
Life Cycle Inventory	**Planning data collection**	• Identify foreground and background data; • Identify relevant processes; • Identify relevant data; • Design Data collection format.

	Collecting unit process	• An actual collection of inventory data is typically only required for the foreground system; • Describing what the modelled unit process represents; • Collect relevant inputs and outputs of the unit process.
	Life Cycle Data Analysis	• Select secondary LCI data sets; • Filling initial data gaps; • Solving multi-functionality of process.
	Calculating LCI result	• Calculate and aggregate inventory data of a system.
Life Cycle Impact Assessment	**Classification**	• Assign LCI results to the selected impact categories.
	Characterization	• Calculate category indicator results.
	Normalization (optional)	• Provide a basis for comparing different types of environmental impact categories (all impacts get the same unit).
	Weighting (Optional)	• Assign a weighting factor to each impact category depending on the relative importance.
Interpretation and Quality control	**Evaluation**	• Identify significant issues;
		• Perform completeness check;
		• Perform sensitivity check;
		• Perform consistency check;
		• Derive conclusion, limitations and recommendations;
		• Check if the LCA results fulfil the goal & scope of study
Reporting		• Is the quality sufficient?
Critical Review		• Are there potential for improvements?

6.2 Goal definition – Identifying purpose and target audience

As the first phase of an LCA, the goal definition[42,43] identifies the decision-context(s) and the intended application(s) of the study; therefore, it exerts a strong influence on all subsequent phases, including interpretation of the final results of the LCA. Figure 7 provides an overview of the key aspects of the goal definition.

[42] ISO 14044:2006 Chapter 4.2.2, http://www.iso-guidelines.com/
[43] ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance", Chapter 5, http://lct.jrc.ec.europa.eu/publications

Figure 7: Goal definition in Life Cycle Assessment – key aspects

When defining the goal of an LCA, it is essential to consider the following aspects:

- **Intended applications.** The intended applications of results shall be stated in a transparent, straightforward and unambiguous manner, so that misleading interpretations are avoided. Particularly important is the decision context;, i.e. is the study meant to (1) support a micro-level decision (e.g., on company, local or regional level), (2) support a nation-wide macro-level decision that would change available infrastructure in a larger extent, or (3) describe a process or present data. The decision context predetermines how the system will be modelled;

- **Limitations to usability of results.** The goal of the study can sometimes imply that limitations exist to the usability of the LCA results. These shall be clearly stated and subsequently reported (see sub-chapter 6.6 on reporting for more information);

- **Drivers & motives.** Drivers and motives for undertaking the LCA shall be made explicit and the decision-context shall be identified;

- **Target audience.** The goal definition shall also identify to whom the results of the study are directed, i.e. the target audience. Different types of target audiences (i.e. “internal” vs. “external” and “technical” vs. “non-technical”) typically imply different scoping requirements for documentation, review, confidentiality and other issues that are derived from the audiences” needs. For LCAs applied to the waste management context, typical target audiences include waste policy-makers at European, national or local levels, waste managers and citizens (e.g., to promote in-house separate collection);

- **Comparisons disclosed to the public.** The goal definition shall explicitly state whether the LCA includes a comparative assertion that will be disclosed to the public[44,45]. This aspect entails a number of additional mandatory requirements under ISO 14040[46] and ISO 14044[47] on the execution, documentation, review and reporting of the LCA due to the potential consequences the results may have for various stakeholders, e.g., external companies, institutions, consumers, etc;

- **Commissioner of the study.** At last, the goal definition shall also identify the commissioner of the study as well as specify all financing and other organizations that have any – potential influence on the study.

6.3 Scope definition – What to analyse and how

During the **scope definition** phase[48,49] the object of the LCA (i.e., the exact system(s) to be analysed) is identified and defined in detail. The choice of the modelling approach (i.e., attributional or consequential – see ILCD for definition and details on implications) is also stated within the scope definition. This shall be done consistent with the goal definition. Figure 8 provides an overview of the key elements of the scope definition phase.

[44] The ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance", Chapter 6.10.1 (http://lct.jrc.ec.europa.eu/publications) defines "comparative assertion" as assertions that, based on LCA analysis, claim the superiority, inferiority or equality of alternatives. The addition "disclosed to the public" means that these conclusions of superiority or equality are published to the general public (i.e., are made available outside a small and well-defined list of actors who were involved in the LCI/LCA study).

[45] All provisions of the ILCD Handbook refer to external use only. In-house decision support by LCA may draw on them but is outside any ruling. "Disclosed to the public" refers here to the accessibility of the study or any of its results, conclusions, or recommendations to an audience outside the commissioner of the study, the involved experts, and any explicitly and individually named limited audience (e.g., an identified list of suppliers, customers, etc.)

[46] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=37456

[47] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=38498

[48] ISO 14044: 2006 Chapter 4.2.3, http://www.iso-guidelines.com/

[49] ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance", Chapter 6, http://lct.jrc.ec.europa.eu/publications

Figure 8: Scope definition in Life Cycle Assessment – key aspects

When defining the scope definition of an LCA, it is essential to consider the following aspects:

- **Defining the functional unit.** A key aim of the scope definition is to define the "functional unit", i.e., the function or the service that the target system provides. When conducting comparative LCA, special attention shall be paid to the definition of the functional unit for each of the systems compared. **In principle, a fair comparison is possible only if all systems compared have the same functional unit**. In practice, this rarely happens due to the existence of co-functions in addition to the main function provided by the system(s) considered. For instance, in case of incineration of MSW with energy recovery (to produce electricity), in addition to the main function of providing treatment to the waste (i.e., waste incineration), the co-service "electricity generation" should be considered and properly accounted. However, from the waste management perspective, the treatment of the waste is the main function that is compared and needs to be specified in detail. Any co-products or co-services (such as power generation) are accounted by crediting the system for the associated avoided environmental burdens (Annex B and Annex C expand on these aspects);

- **Setting the system boundary**. The system boundaries define which parts of the life cycle and which processes belong to the system, i.e., are required to provide its function as defined by its functional unit (Annex B and Annex C expand on these aspects);

- **Defining cut-off criteria**. Not all processes and elementary flows are quantitatively relevant: for the less relevant ones, data of lower quality ("data estimates") may suffice, decreasing the overall study effort. Irrelevant data can be entirely **cut-off**[50];

- **Selecting the time horizon**. The time horizon expresses the period during which all the environmental aspects (e.g., inputs and outputs) are considered, i.e. the accounting period. The choice of the proper LCA time horizon is a compromise between the need to cover most (virtually all) of the emissions and the availability of sufficiently accurate data throughout this time.
- **Data quality & sources**. For identifying the data and information needs and suitable sources, the required overall data quality is the key measure. This can be derived directly or indirectly from the goal of the LCI/LCA. Data quality is composed of accuracy (i.e., adequate technological, time-related and geographical representativeness, methodological appropriateness and consistency), precision / uncertainty, and completeness of the inventory;
- **Planning reporting**. Unbiased and transparent reporting is a vital element of any LCA. Without clear and effective documentation for the experts and clear communication with decision-makers, LCAs may be misused or can be misleading and, therefore, may not contribute to improving environmental performance.
- **Identifying critical review need.** A critical review shall be performed by experts who have not been involved in designing and conducting the LCI/LCA study, including report preparation. Expert review generally improves the study/report quality and the credibility of its findings, hence increasing the value of the study. This also applies to in-house applications, where there may be no formal requirement for a critical review. The required type of critical review (e.g., independent internal review, independent external review, (external) panel review, etc.), depends on the intended applications of the LCI/LCA study. In the ILCD Handbook this is defined in the separate document “Review schemes for LCA”[51].

6.4 Life Cycle Inventory (LCI) – quantifying resource consumption and emission

The life cycle inventory modelling phase[52] focuses on the data collection and system (e.g., product) modelling. These tasks must be consistent with the goal definition and meet the requirements determined in the scope phase. The LCI results provide the input data for the subsequent LCIA phase. Figure 9 provides an overview of the key elements of the inventory phase.

[50] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 6.6, http://lct.jrc.ec.europa.eu/publications
[51] http://lct.jrc.ec.europa.eu/assessment/projects
[52] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 7, http://lct.jrc.ec.europa.eu/publications

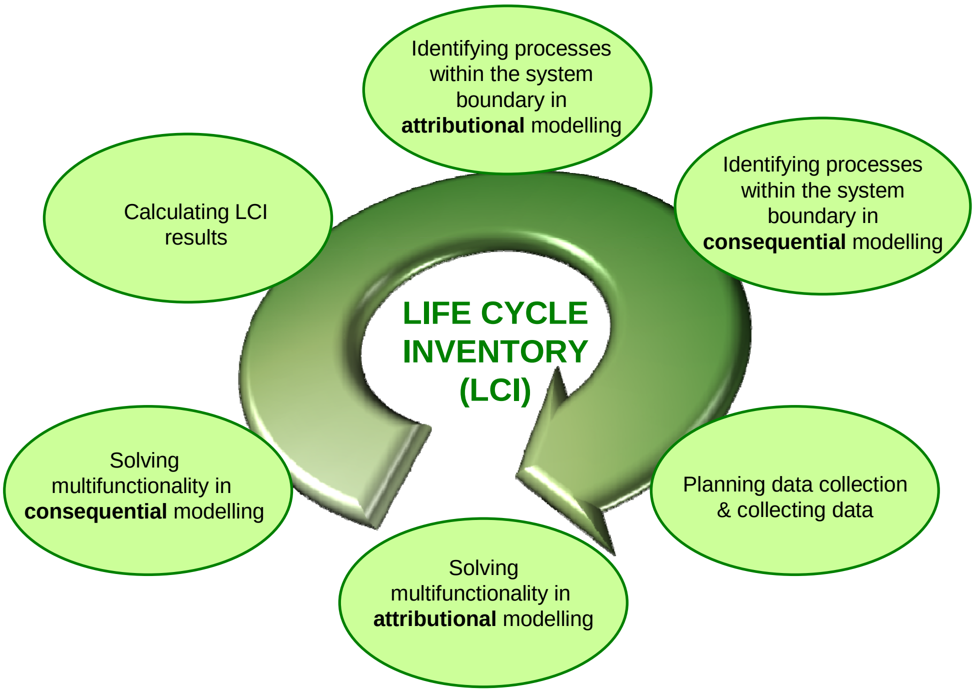

Figure 9: The Life Cycle Inventory phase in Life Cycle Assessment – key aspects

The LCI phase (including data collection, acquisition, and modelling) generally requires the greatest level of effort in an LCA. The specific kind of LCI work depends on the study deliverable; not all of the following steps are required for all LCAs. In its entirety, life cycle inventory work means:

- **Identifying processes in attributional / consequential modelling.** Identifying the processes that are required in the system: different methods exist to identify processes within the system boundary depending on the modelling principle that will be used, attributional or consequential. This choice depends on the decision context of the study. More information is given in Annex C4;
- **Planning data collection & collecting data.** Planning collection of raw data and information, and of data sets from secondary sources. Collecting unit process inventory data for processes (typically) of the foreground system. An important aspect is the interim quality control and how to deal with missing inventory data;
- **Solving multifunctionality in attributional / consequential modelling.** For micro-level decision support and accounting/monitoring cases, subdivision of multifunctional processes is preferable, followed by substitution/system expansion of avoided burdens. Finally, as last option allocation is used to exclude existing interactions with other systems. Consequential modelling in macro-level decision support uses subdivision and then substitution/system expansion (see Annex C for more details).
- **Calculating LCI results**. This means summing up all inputs and outputs of the same elementary flows and all processes within the system boundaries.

More details on the LCI step are provided in Annex B. However, due to the complexity of this step, the ILCD Handbook should serve as the primary reference.

6.5 Life Cycle Impact Assessment (LCIA) – quantifying potential environmental impacts

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inputs and outputs that have been compiled in the inventory are translated into impact indicator results related to human health, natural environment and resource depletion[53,54,55].

There are approximately 10 widely used environmental impact categories that can be used to cover the main environment/ health issues. The following list provides a summary of the most frequently used impact categories[56]. There are a range of alternative LCIA methods available for calculating impacts in these categories. Guidance on impact assessment indicators, their derivation and approved methods can be found in the ILCD Handbook – Recommendation of methods for LCIA[57].

Examples of generally used environmental impact categories (non exhaustive list):

- Climate change;
- Ozone depletion;
- Human toxicity;
- Particulate matter / Respiratory inorganics;
- Ionizing radiation;
- Photochemical ozone formation;
- Acidification;
- Eutrophication;
- Ecotoxicity;
- Land use;
- Resource depletion;
- Other impacts not generally considered, e.g., noise, accidents, desiccation, erosion, salination.

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53 Reference to ISO 14044:2006, chapter 4.3.3

54 ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 8, http://lct.jrc.ec.europa.eu/publications

55 ILCD Handbook, “Framework and requirements for Life Cycle Impact Assessment (LCIA) models and indicators”, http://lct.jrc.ec.europa.eu/publications

56 European Commission - Joint Research Centre - Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook - Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in a European context. Publications Office of the European Union; in publication, 2011. Will be available online at http://lct.jrc.ec.europa.eu/assessment/projects

57 http://lct.jrc.ec.europa.eu/assessment/projects

Working environment (and other social issues) and accidents are outside the scope of most LCAs, but they can be addressed analogously using parallel analysis and be jointly used to improve the decision support on environmental and human health questions.

The LCIA phase consists of mandatory steps (classification and characterisation) that lead to LCIA results in the above-listed impact categories, and optional steps (normalisation and weighting) that can be used to further aggregate them. Figure 10 provides an overview of the key elements of the LCIA phase, while more information on the LCIA step is provided in Annex B.

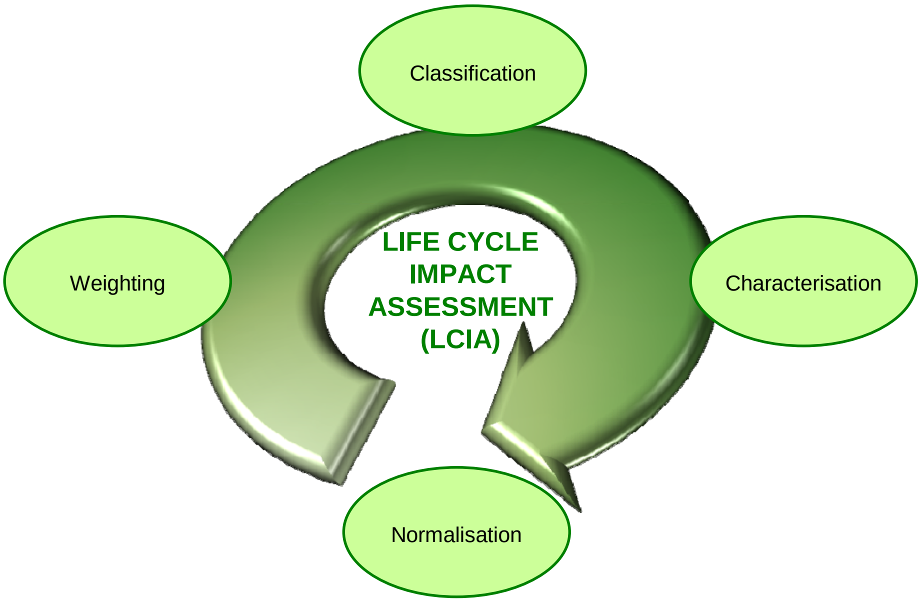


Figure 10: The Life Cycle Impact Assessment (LCIA) phase in Life Cycle Assessment (LCA) – key aspects

The following aspects should be considered for the LCIA:

- Based on **classification** and **characterisation** of the individual emissions and resources consumed, the LCIA results are calculated by multiplying the individual inventory data of the LCI results with the characterisation factors;
- **Classification** involves assigning the elementary flows to the one or more relevant categories of impact. **Characterisation** involves a multiplication of the individual elementary flows with the relevant impact factors (i.e., characterisation factors) from the applied LCIA method. The “characterisation factors” express the individual contributions to the impact factor of each elementary flow relative to a reference flow (e.g., the characterisation factor of methane (CH_4) for the impact category climate change is equal to 25 kg CO_2-equivalent – IPCC 4th Assessment Report);
- The LCIA results per impact category have different units. Therefore, they cannot be compared directly to identify which are most relevant factors. Similarly, the numerical ratings for each impact category cannot be added to develop a comprehensive LCIA ranking;

- **Normalisation** is a subsequent, optional step, in which the LCIA results are multiplied with “normalisation factors” that represent the overall inventory of a reference (e.g., a whole country or an average citizen), obtaining dimensionless, normalised LCIA results. Normalised LCIA results reflect only the contribution of the analysed product to the total impact indicator but not the relative severity/relevance of the impact to others. Therefore, also the normalised LCIA results must not directly be summed. But, they can provide insights into the relative importance of a impact in a given impact category;
- **Weighting** is another optional step which subjectively assigns weights/relevance factors to each of the different environmental problems,. LCIA results (eventually as normalised results) are multiplied by the associated “weighting/relevance factors”, yielding “weighted” LCIA results. These weighted LCIA results can be added together and the sum provides a single-value overall impact indicator. Weighting allows for comparing directly, or summing up, results across impact categories where this cannot be otherwise achieved using natural science approaches.

6.6 Interpretation of results[58,59]

Figure 11 presents the key elements that should be considered for interpreting the results of an LCA. More related information is provided in Annex B.

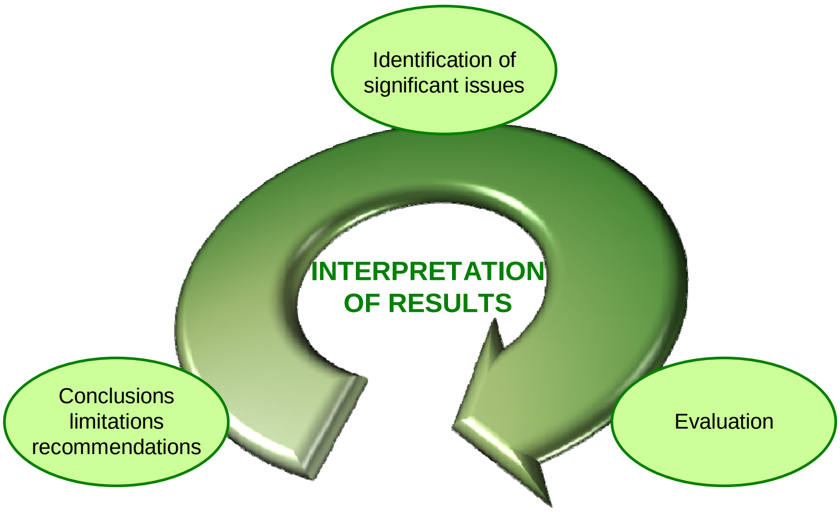


Figure 11: Interpretation of results in Life Cycle Assessment – key aspects

The interpretation proceeds through three activities:

- **Identification of significant issues[60]**: The purpose of this first element is to analyse and structure the findings of earlier phases of the LCA to identify the significant issues. These can be among the following: inventory items, impact

[58] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 9, http://lct.jrc.ec.europa.eu/publications
[59] Refers to ISO 14044:2006 chapter 4.5
[60] Refers to ISO 14044:2006 chapter 4.5.2 and to aspects of 4.4.4

categories, modelling choices, methods assumptions, commissioner and interested parties, etc. The analysis of the previous steps may lead to some revisions. The final LCA results might thus be obtained through multiple iterations of LCA phases;

- **Evaluation[61]:** The evaluation element provides the basis for reaching substantive conclusions and developing recommendations. It is based on interpretation of the LCA results and is done in accordance with the goal and scope of the LCA. It involves three levels of checks:
    1. Completeness check on the inventory: this step determines the degree to which the inventory is complete and whether the cut-off criteria have been met;
    2. Sensitivity check: this step assesses the reliability of the final results, conclusions and recommendations. Consideration of the impacts of the key assumptions made throughout the study (e.g., time horizon, energy mix of reference, etc.) on the final results is a key element of this step ;
    3. Consistency check: this step investigates whether the assumptions, methods, and data have been applied consistently in terms of accuracy, completeness and precision throughout the LCA;
- **Conclusions, limitations and recommendations[62]:** Integrating the outcome of the other elements of the interpretation phase and drawing upon the main findings from the earlier phases of the LCA, the final element of the interpretation is to formulate the important LCA conclusions, to identify the key limitations of the LCA and to develop recommendations for the study audience that are consistent with the goal definition and the intended application/purpose. Note that this last step is optional, e.g., in case of data development or reporting of the environmental performance of a single waste treatment system, this step is not necessary involved.

[61] Refers to ISO 14044:2006 chapter 4.5.3
[62] Refers to ISO 14044:2006 chapter 4.5.4

7 Technical Guidelines on Waste-Type Specific Management Planning

What is the focus of this chapter?

This section builds upon the general guidance given in the previous chapters. It provides technical guidance on how to approach waste management planning at the level of individual waste streams. This may help e.g. public authorities develop waste-type specific management planning and guidelines[63].

Who should read it?

This chapter is aimed at waste policy-makers, waste managers and civil servants supporting public decision makers who want to conduct waste-type specific assessments and management planning.

The preceding sections of this general waste guidance document provide the key elements to help support decision-making related to the overall municipal solid waste. However, due to the high heterogeneity of the waste, similar support is needed for specific waste fractions. The general LCT/LCA-based guidance given in the previous chapters of this document needs thus to be complemented with technical guidance at the level of the individual waste streams.

This chapter is intended to provide waste policy-makers, waste managers and civil servants supporting public decision makers with the insights necessary to approach waste management planning for individual waste streams as opposed to the overall municipal solid waste. In particular, waste-type specific guidance is here provided to help:

1. Identify and characterise the target waste stream(s) in relation to the environmental priority actions needed (Chapter 7.1);
2. Formulate the specific waste management issue(s), assess whether evidence from existing knowledge is sufficient to address the issue(s), and determine if straightforward criteria apply (Chapter 7.2);
3. Identify Key Environmental Data and Modelling Assumptions (KEDMA) to help conduct a new LCA (Chapter 7.3);
4. Identify geographical differences and integrate them within the modelling framework (Chapter 7.4).

[63] The Joint Research Centre (JRC) in cooperation with the Directorate General Environment (DG ENV) , based on the guidance given in this chapter, developed two waste-type specific guidelines, namely a "Guide to Life Cycle Thinking and Assessment in the context of Construction and Demolition (C&D) waste management for waste policy-makers and waste managers" and a "Guide to Life Cycle Thinking and Assessment in the context of Bio-waste management for waste policy-makers and waste managers"

7.1 How to identify and characterise the target waste stream

7.1.1 Identification of target waste stream(s)

- The first stage of the development of waste-type specific management planning is the identification of one or more target waste streams. These can, for instance, be identified as those streams that provide the greatest potential for environmental improvements based on the current situation. The overall environmental impact/benefit of managing a certain waste stream depends on several factors, including the intrinsic properties of the waste stream(s), e.g. waste composition (especially in relation to the concentration and mobility of hazardous elements / compounds, e.g., heavy metals, toxic substances), physical state (e.g., solid, liquid), etc.;
- The amount of waste generated (e.g., tonnes/year or tonnes/person/year);
- The existing legislation/regulations governing the handling / treatment of the waste stream;
- The existing handling / treatment options (re-use options, recycling options, incineration, etc.) and the differences in the specific environmental performance of these options (e.g., energy recovery efficiency, emissions levels, etc.);
- The overall potential of the specific waste stream(s) to serve a substitution role (e.g., only energy recovery or recycling or both).

For some waste streams, existing legislation gives clear directions on the applicable handling and treatment strategies/option(s). For example, this is the case of packaging waste (Directives 85/339/EEC, 94/62/EC and 2005/20/EC). However, regardless of the legislative directives provided, a thorough LCT/LCA-based investigation can generally help improve the existing waste management strategy.

On the other hand, when the existing legislation on the management of a given waste stream does not give comprehensive and conclusive directions, LCT/LCA-based guidelines should be developed to help identify the environmentally preferable option. These guidelines would in turn also provide policy-makers with robust, science-based support for developing more environmentally sustainable waste policies.

Until the Landfill Directive (1999/31/EC) was put into force, the main management option for bio-waste was landfilling. However, landfilling of bio-waste in poorly engineered landfills, has led to substantial emissions of methane and other greenhouse gases to the atmosphere, as well as discharge of contaminated leachate to surface water and groundwater. To reduce methane emissions (and other greenhouse gases) from landfills, the Landfill Directive prescribed progressive reduction of biodegradable waste lanfilling (bio-waste constitutes a large fraction of the overall biodegradable waste). However, the Landfill Directive does not give conclusive guidance on how to handle the biodegradable waste diverted from landfills.

Several pieces of legislation dealing with bio-waste exist in addition to the Landfill Directive (e.g., Waste Framework Directive, 2008/98/EC; Commission Communication on future steps in bio-waste management in the European Union, COM(2010)235), but the associated legislative directions do not comprehensively cover all the waste management options. For example, the intrinsic properties of bio-waste allow for both energy recovery (e.g., through anaerobic digestion) and recycling (e.g., through composting and use of compost on land), which when implemented can bring marked environmental benefits compared to conventional landfilling. Another example, which entails both energy recovery and recycling, is co-processing in cement plants (i.e., when waste contains both a combustible fraction like plastics and a mineral fraction like aluminium hydroxide, a component of cement).

Construction and Demolition (C&D) waste can be extensively recycled. The non-recyclable part consists primarily of inert fractions (e.g. plastics, concrete, and asphalt) that could in theory be disposed of in landfills without causing significant environmental impacts per unit mass landfilled. However, the very large amount of C&D waste generated yearly makes it necessary to optimise strategies for C&D waste handling to reduce the landfill disposal capacity that is devoted to C&D wastes. This highlights the fact that even inert waste streams can exert environmental pressures (e.g., destruction of natural habitat to create landfill space) by their disposal or treatment.

In summary, waste stream attributes (such as specific properties of waste stream, the amount generated, and the existing legislation and treatment facilities) should be considered to identify the contexts where waste-type specific management planning founded on LCT and LCA should be developed.

7.1.2 Characterisation of the target waste stream

To use LCT and LCA to help address waste-type specific management issues and planning, requires a thorough understanding of the of the subject waste stream properties.

Developers of waste-type specific management planning may:

- Provide default chemical composition for the targeted waste (and clearly specify the unit), e.g.,
    - Organic content;
    - Carbon content: total, biogenic, fossil;
    - Moisture content;
    - Nitrogen, Phosphorous, Potassium content;

  - Inert mineral content;
  - Heavy metal content, with separated details for each major heavy metals (e.g., Cd, Co, Ni, Pb),
- Provide low heating value (LHV) for the targeted waste and clearly specify the unit;
- Estimate the content of steel, aluminium, copper available for potential recovery;
- List the relevant components and physical/chemical parameters of the wastes; the example for bio-waste is provided in the following table:

Table 3: Example of Relevant parameters for bio-waste composition

Relevant composition parameters	In relation to
Nitrogen (N), Phosphorous (P), Potassium (K)	Application as compost / fertiliser
Carbon (C): total, biogenic, fossil	Lower heating value and soil improver
N/C ratio of end product	Indication of maturity of compost
Water content	Lower heating value
Heavy metal content	Indicator for applicability in agriculture

- Provide default fraction distribution for the targeted waste stream e.g., fraction of plastics, paper, metals for recovery, etc.;
- Provide a list of applicable methods to perform a solid waste component analysis and a list of the main crucial choices (e.g. focus on humidity and calorific value if a key treatment is energy recovery; focus on heavy metals and nutrients (NPK) if a key treatment is composting) when performing a solid waste component analysis;
- Provide default data on the amount of waste generated according to the type of geographical area (urban, rural, etc.).

Example: Characterisation of Construction & Demolition waste

Characterisation of Construction & Demolition (C&D) waste can be approached differently within different contexts. For instance:

- From a **site waste contractor perspective**, visual inspection of the waste stream and other rudimentary waste compositional analysis may be sufficient to provide an indication of the material content of the specific waste stream. Structured sampling techniques may follow, which can help to determine the properties of the “typical” waste stream. These may even consider how the material content may vary in the future. Further analysis may be necessary for some waste streams. For example, if there is a suspicion that the waste stream may possess hazardous properties or have other potentially deleterious impacts, physico-chemical analysis may be necessary.

- **Policy managers** may rely on published information concerning the properties of typical C&D waste streams, such as regional estimates for the composition of the waste stream. Caution is warranted when using such data, since these may be either based on statistically robust estimates covering different C&D waste streams and their sources, or on ad-hoc rudimentary sampling/estimates. Obtaining specific information relevant to the local, regional or national area concerned is always recommended.
- **Building designers**, and those responsible for specifying material choices, will have good insight into the materials imbedded within a structure and have ultimate control over the future composition of the associated wastes. Consideration should be given to the ease of, and potential for, managing these materials at the end of their lifetime. For example, the inclusion of hazardous components may prevent direct re-use or recycling and recovery opportunities. It is important to remember that the full life cycle of any design choice must be considered, so that actions targeted at end-of-life waste management do not lead to increased environmental impacts elsewhere, for example in producing materials or operating buildings.

7.2 How to approach waste-type specific management issues

7.2.1 Formulating the right questions

Waste-type specific management planning should help formulate in a straightforward manner the specific questions that need to be answered to support waste management decision-making. For example:

- Should measures be introduced to reduce the amount of plastic waste going to landfills?
- Can emissions from the separate collection of recyclables be reduced?
- What can be done to make the management of Construction & Demolition (C&D) waste more environmentally sustainable?

After the waste management issues have been formulated, it becomes possible to identify the different options that can address each issue. This allows reformulating the questions in a more precise manner. For instance, the three questions formulated above could be rephrased as follows:

- Is it preferable (for environmental reasons) to landfill a given type of plastic depending on its purity and composition, to recycle it, or to combust it and recover the combustion energy?
- Is it better for the environment to collect recyclable waste components door-to-door or to ask citizens to drop their waste in dedicated collection

points (e.g., bottle banks) from which the material is afterwards removed by the waste authorities?

- Would C&D waste management become more environmentally-sound if recycling was maximized or if instead the priority was given to landfilling in nearby special landfill for C&D waste?

Particular care is needed when scenarios are investigated which change the composition of (residual) waste streams. Trade-offs in other than the assessed waste may well be of significant relevance for overall results (e.g. residues from selective collection are valorized in cement kiln while, if not collected selectively, they would be landfilled; this means that an indirect consequence of selective collection is a change in treatment of a fraction of another waste stream).

7.2.2 Finding the proper approach to support decision-making

When planning management strategies for specific waste streams, it is key to assess whether there is sufficient knowledge and evidence available to identify significant environmental differences among the considered waste management options.

In some cases, the answer is clear and supported by the waste hierarchy principle. For instance, preventing waste generation is always the best choice when waste prevention does not adversely influence other aspects of the product"s life cycle. Likewise, waste re-use is usually assumed to be a better option than waste disposal. In other cases, screening of available information will be sufficient to develop a clear picture.

As outlined in Chapter 4, conducting an LCA to support decision-making in waste management may not always be needed. There may be instances in which evidence from previous work is sufficient to support decision-making or when simple, straightforward criteria are sufficient to unambiguously identify the environmentally preferable management option for the subject waste stream.

When robust studies on comparable issues do not exist or are not available, then conducting an LCA may be needed. This can be decided by considering carefully the following aspects:

- The actual potential for environmental trade-offs or burden shifting resulting from the decision that needs to be taken;
- The extent to which the decision may affect multiple stakeholders and interested parties;
- The extent to which the decision may affect the market or have other consequences, e.g., technological lock-in;
- The extent to which the waste stream(s) involved in the assessment may pose threats to the environment or human health.

7.2.3 From the waste hierarchy to straightforward criteria

As outlined in Chapter 4.3, straightforward criteria can sometimes be sufficient to support waste decision-making. Waste-type specific management planning should help develop waste-type specific criteria for simple, yet tailored, support to decision-making.

Developing and using straightforward criteria can be a valuable step in between applying the waste hierarchy and conducting a new LCA. For instance, the waste hierarchy applied to bio-waste management reads as shown in the next figure.

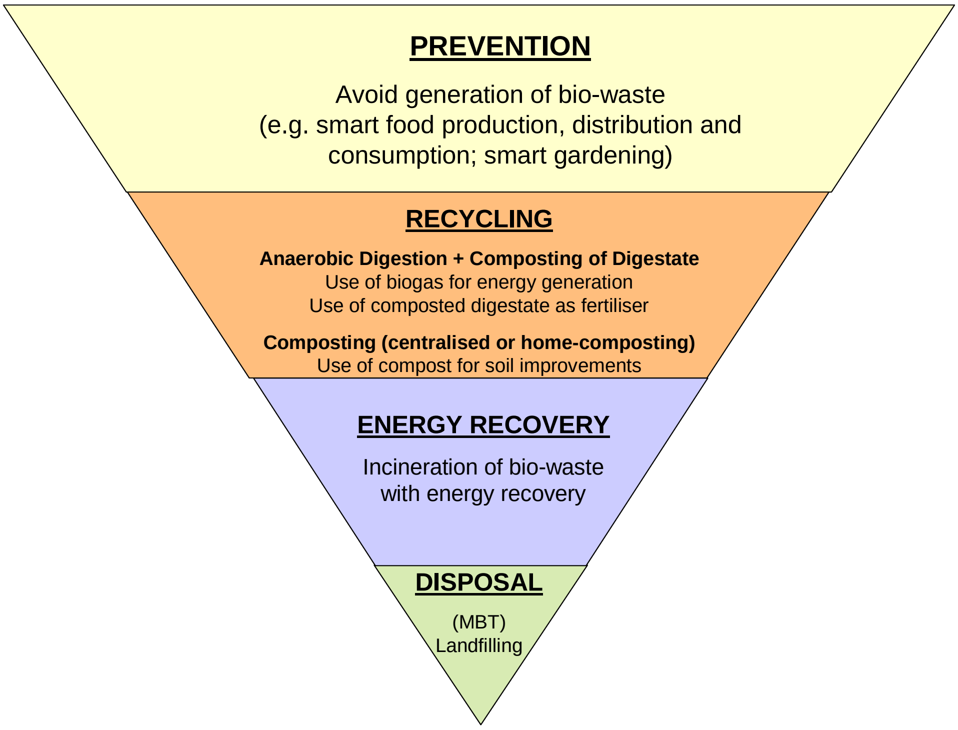


Figure 12: The "waste hierarchy" applied to bio-waste management

Straightforward criteria often can be derived from the available experience and knowledge gained from previous successful applications of LCT and LCA to comparable waste management contexts. Moreover, it needs to be ensured that all relevant waste management options for the specific waste stream are identified and evaluated in a systematic and consistent way to ensure a fair comparison.

Example: Deriving straightforward criteria for C&D waste management

LCT/LCA-based guidelines for Construction and Demolition (C&D) waste guidelines should help identify the key elements to develop specific straightforward criteria. These include:

- **Re-using materials and components.** Wherever possible, seek opportunities to separate and directly re-use materials on- or off-site.
- **Materials in the waste stream with high embodied impacts.** Where metals (e.g., aluminium, steel, copper) are present in sufficient quantities in a mixed C&D waste stream, separation for recycling is likely to be the best environmental option.

- **Readily combustible materials derived from biomass.** WRAP (2010)[64] indicates that combustion can be a preferred route for wood if it can be readily separated and energy recovery is maximized (producing electricity and heat).
- **Remaining inert fraction (e.g., stone-waste).** A recent study investigating the environmental impact of the disposal of construction waste in Catalonia[65] suggested that stone wastes are more suited to recycling when the recycling plant is close to the building site. Re-use of stone as a gravel replacement on building sites is generally the best environmental option for stone waste.

7.3 How to identify Key Environmental Data and Modelling Assumptions (KEDMA)

7.3.1 Overview

Generally, a limited number of Key Data and Modelling Assumptions (KEDMA) have a significant influence on the results and conclusions of an LCA.

Depending on the number of impact categories, the size of the system being assessed and the required precision, roughly about 30 to 60 emission flows and resource consumptions (e.g., 5 to 10 per impact category), and 2 to 5 modelling assumptions need to be carefully and thoroughly:

- researched (primary data),
- analysed (representativeness: geographical, temporal, technical, precision),
- discussed (sensitivity analysis), and
- possibly presented together with the main results and conclusions

in order to show and explain the sensitivity of the results and conclusions to those KEDMA for the specific waste stream.

Those data are purely indicative and, in some cases, the number of relevant items might be significantly smaller. However, this also highlights that for many processes secondary data are adequate for most elementary flows and specific primary data search can be limited to a very small number of elementary flows, thereby, limiting the overall data collection effort.

For other data and assumptions, estimates or data from databases (even if not absolutely consistent with required representativeness) may be sufficient (e.g., if only 2% of a waste stream – a residual stream- is incinerated with energy recovery, the efficiency of the energy recovery does not need to be determined precisely).

64 WRAP (2010) Environmental Benefits of Recycling – 2010 Update. WRAP, Banbury, UK.
65 http://ec.europa.eu/environment/integration/research/newsalert/pdf/191na4.pdf

7.3.2 Recommendations

When conducting waste-type specific management planning it is important to:

- Identify all relevant KEDMA (KEy Data and Modelling Assumptions);
- Provide indicative value ranges for the identified KEDMA;
- Provide relevant data sources for KEDMA;
- Indicate when primary data related to the specific waste stream and its treatment is necessary because available data are not of sufficient precision/quality;
- Provide attention points about KEDMA (e.g., for bio-waste: distinction between wet weight and dry weight, between lower heating value and higher heating value, etc.).

Modelling assumptions should be consistent with the general methodology applied. Particular attention should focus on the indirect effects (see for instance the following example).

Example: Use of compost on land

A composting process produces compost; using this compost has different effects (consequences) that depend on:

- The compost composition (amount N, P, K, organic composition and thus stability);
- How it is used (in gardens, in fields, etc.);
- What actions/effects would occur if this compost were not available (substitution), e.g.,:
    - no compost used at all (➔ model the effects on growth, on NPK use, on water consumption, etc.);
    - using compost from elsewhere (then look if there is a further substitution: is there another place where compost is not used anymore and what are the effects there? Is there an increased selective collection of organic matter elsewhere and an increased compost production?);
    - using peat (then look at the effects of using peat) or other soil improvement matter.

The main indirect effects should be listed, described, documented and discussed.

7.4 How to identify geographical differences and integrate them within the LCA modelling

7.4.1 Overview

The environmental performance of waste management processes is influenced by general factors that may exhibit geographical variations. These factors should be carefully considered when carrying out waste-type specific management planning, as they may also differ greatly among different waste streams. These factors include:

- Existence and location of potential markets for waste or recovered products from waste;
- Institutional factors;
- Economic and social factors;
- Technical factors.

7.4.1.1 Natural geographical factors

Climate

Climate zone influence on the environmental performance is commonly not modelled in databases and, therefore, is not applied by LCA practitioners. However, when this parameter can play an important role, it should be taken into account in the modelling and calculations. For example, one should consider the great influence that climatic conditions exert on the collection frequency of source-separated biodegradable waste.

Water availability

Depending on the regional situation, water availability may vary greatly. Some regions have acute water scarcity, whereas, others have an abundance of water. In regions with limited water resources, the use of water is more problematic than in other regions. Water-consuming processes (e.g., washing plastics before recycling) should be limited in regions where water shortages are prevalent.

7.4.1.2 Institutional factors

Legal framework

In addition to the European Landfill Directive (1999/31/EC) and the Waste Framework Directive (2008/98/EC), Member States are obligated to comply with national regulations and policies on waste management. Important national regulations include quality standards for recovered material, e.g., packaging or compost that differ markedly countries.

Political decisions

Political goals regarding waste management and the environment may change over time and may differ regionally. For instance, the goal of reducing certain emissions that contribute to climate change is currently a top priority. This may influence the relative importance given to other impact categories, such as toxicity effects and eutrophication.

7.4.1.3 Economic and social factors

Fertility of soils (this is also an environmental issue)

Soil organic matter content varies greatly among regions, mainly as a function of climatic conditions. In regions with poor soils (lower in organic content), soil amendment with compost and organic residue (e.g., peat) is necessary to improve soil fertility. In these areas, especially those areas with depleted peat resources, compost production should be a priority compared to regions where soil fertility is adequate.

Existence and location of potential markets for recovered products from waste

In waste management, availability of outlets for recovered products (e.g., compost, biogas, etc.), or recovered energy, are key factors that positively influence the overall environmental performance of waste management. The latter also depends on various socio-economic factors, such as potential customers, substitution rate, type of applications, compliance with standards, and markets for the end products from treatment. A favourable price is a market incentive favouring recycling.

Social habits and consuming habits

Social habits (e.g., the willingness of citizens to properly handle the waste produced at their households) and consuming habits influence the environmental performance of waste management strategies. Both should therefore be considered when developing waste-type specific guidelines.

Example: Household waste composition changes among regions

For instance, in Mediterranean areas, the relative high content of fermentable waste in household waste is due to[66], e.g.:

- the large fraction of vegetables and fruits in the daily diet and in the preparation of meals;
- the effect of tourism generating a high fraction of waste from meals, compared to strictly residential consumption;
- the reduced use of food packaging---because of a less wealthy economy;
- the lower use of pre-cooked or frozen products.

[66] Drivers for separate collection in the EU, optimisation and cost assessment of high capture schemes," E. Favoino, VI European Forum on Resources and Waste Management, Valencia, Spain 6-7 June 2002.

7.4.1.4 Technical factors

Availability of waste treatment facilities

Local availability of treatment facilities - in terms of type, distance and capacity – is a crucial issue influencing waste management strategies. These strategies may deviate from the priority order indicated by the "waste hierarchy" depending on what waste treatment infrastructures exist in the target region.

Availability of transport infrastructures

The local availability and type of waste transport infrastructure also exert an influence on waste management strategies.

7.4.2 Requirements

When conducting waste-type specific management planning it is important to:

- Identify and list those relevant factors that could influence the targeted waste stream;
- Carefully consider that these factors may change from region to region;
- Based on the identified factors, identify which of KEDMA also change from region to region; for these, a more detailed assessment may be required.

7.4.3 Remarks and examples

As discussed, natural, institutional, economic and technical factors have an important affect on the development waste management systems. The following tables expand on the influence exerted by these factors.

For collection and transport:

Table 4: Influence of geographical, institutional & technical factors for collection & transport

Geographical	Climate may play a crucial role related to the decision of waste **collection frequency**. Depending on temperature and/or humidity, bio-waste waste collection frequency is adjusted to prevent odour or hygiene problems from waste decomposition in the collection containers. For example, collection frequency of food waste may change from weekly in fall through spring, to daily in the summer for Southern areas. Waste-type specific guidelines for bio-waste management should consider this aspect carefully.
Institutional	Euro emission standards set maximum limits for pollutant discharges from vehicles and may influence the viable **mode(s) of transportation** (e.g., EURO 3 truck, railway transportation, cargo-ferries, etc.) selected for a specific waste management strategy. Waste-type specific guidelines for waste streams that need to be transported for long distances should consider this aspect carefully.

Technical	If local waste treatment facilities are unavailable, long distance transport by waste-trucks is likely. This leads to issues concerning transportation-related fuel emissions and issues related to bio-waste degradation inside the trucks. Waste-type specific guidelines for waste streams that need to be transported for long distances should consider this aspect carefully, especially for biodegradable waste types.

For biodegradable waste:

Table 5: Influence of geographical factors for biodegradable waste

Geographical	Climate may influence significantly those waste treatment methods that require a certain working temperature, such as anaerobic digestion and gasification. A higher energy input is necessary to run these treatment methods in cold climates. Increased energy consumption can reduce the overall environmental performance of the treatment method. LCT/LCA-based guidelines for biodegradable waste types should carefully consider the climate influence on the treatment methods.

8 How to Get Started with LCA on Waste Management

What is the focus of this chapter?

This section provides general methodological guidance on how to start a new LCA applied to waste management. This involves identifying the proper decision-context situation, the minimum modelling requirements and the available sources of data.

Who should read it?

This chapter is aimed at LCA practitioners who want to conduct an assessment involving waste management systems and strategies.

8.1 Possible decision-context situations

As a starting point, the specific context related to the target waste management system shall be identified. This shall be done during the goal definition phase. According to the ILCD Handbook[67], it is possible to identify three different decision-context situations (Situations A, B and C) that are of practical relevance in LCA.

Table 6: Identification of the decision-context

<table>
<tr><td rowspan="4">(Direct) decision support?</td><td rowspan="3">Yes</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A
"Micro-level decision support"</td><td>Situation B
"Meso/macro-level decision support"</td></tr>
<tr><td>No</td><td colspan="2">Situations C1 and C2
"Accounting/Monitoring"</td></tr>
</table>

The decision-context (including the scale of changes in the background system that will result from the decision) determines both:

- The appropriate LCI modelling framework (i.e., “attributional” or “consequential”). Annex C4 expands on this;
- The related LCI method approaches (i.e., “allocation” or “substitution”). Annex C5 expands on this.

The decision-context also influences:

- Inventory data collection and modelling;
- Calculation of impact assessment results;
- LCA result interpretation.

[67] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 5.3, http://lct.jrc.ec.europa.eu/publications

8.1.1 Micro-level decision support (Situation A)

8.1.1.1 General

Situation A typically involves single technology analysis, sites/companies, local/regional studies with no consequences (or only small-scale ones) on the background system or other systems. This means that the consequences of the analysed decision alone are too small to affect structural changes of installed capacity elsewhere.

8.1.1.2 Situation A applied to waste management

Situation A refers to decisions supporting direct changes (optimisation) in the waste management system at a local, regional, or plant-specific level. It covers the following LCA applications:

- Identification of Key Environmental Performance Indicators (KEPI);
- Weak-point analysis of a specific system;
- Detailed Ecodesign / Design-for-recycling;
- Assessment of new treatment routes;
- Comparison of specific services (e.g., waste management system route);
- Benchmarking of specific technologies against the technology group average;
- Development of the “Carbon footprint”, “Primary energy consumption” or similar indicator for a specific waste treatment process;
- Development of specific, average or generic unit process or LCI data sets for use in Situation A.

The decisions resulting from this type of LCA will have only small-scale consequences on the system (e.g., no sudden large additional demand for recycling facilities results; national market prices for secondary materials remain unchanged).

Typical goals include:

- Selection of a treatment route from several alternatives for a specific waste stream among alternatives;
- Selection of a specific waste stream to treat;
- Optimization of existing treatment routes.

Examples:

- A city wishes to build a new treatment plant for its municipal solid waste (MSW) and, is required to also accomplish the recycling target. What is the best option among:

  - Mechanical Biological Treatment (MBT)?
  - Incineration with energy and metals recovery?
  - Plasma treatment?
  - Pyrolysis treatment?
- A municipality wants to know how to improve its selective collection system for packaging.

Note: the same type of example as for European and National level should be presented for multi-system analysis or contribution- or weak-point analysis.

With respect to the plant-specific level, the target audience is mainly private companies active in local waste management, e.g., plant manager, waste management operator. The decisions resulting from this type of LCA will have only small-scale consequences on the system.

A typical goal is optimization of existing treatment routes, i.e., identification of the most environmentally significant processes during waste treatment routes. For instance:

- Variants of a waste sorting line system design, e.g., trommel followed by a densimetric table or a ballistic separator;
- A contribution or weak-point analysis of a specific system, e.g, a given biological treatment of waste;
- Assessment of types of fuel for a collection vehicle: diesel, gasoline, electricity, biogas (e.g., for a collector);
- Assessment of anaerobic digestion plants for treatment process improvement (residence time, autoconsumption, etc.).

8.1.2 Meso/macro-level decision support (Situation B)

8.1.2.1 General

Situation B typically involves decision support for strategies with large-scale consequences on the background system or other systems. The effects of target decision are significant enough to cause structural changes of installed capacity of at least one process outside the foreground system of the target system. Note that small-scale marginal consequences are covered under Situation A and shall not be interpreted as *per se* resulting in large-scale consequences on installed capacity.

8.1.2.2 Situation B applied to waste management

Situation B applied to a given waste management system should cover the following LCA applications:

- Policy development: forecasting & analysis of the environmental impact of planning and programming, waste management strategies, etc;
- Policy information: identifying services or service groups with the greatest environmental improvement potential;
- Development of datasets: specific, average or generic unit process or LCI data sets for use in Situation B.

Note that life cycle inventory (LCI) data sets for use in Situation A are also required for those parts of the background system of Situation B that are not affected by any large-scale consequences, i.e., typically most of the processes that have a smaller affect on the overall results. The future-scenario unit process data sets are the same for Situation A and Situation B, inasmuch the specific process / technology is required in both cases.

It is important to note that the LCI modelling provisions for Situation B refer exclusively to those processes that are affected by these large-scale consequences and that the other parts of the life cycle model shall be modelled as Situation A.

Remarks and examples

Situation B refers to decisions supporting the direct elaboration of a strategy related to waste management.

The target audiences are European or national political decision makers and other stakeholders of the waste management sectors (e.g., NGOs, federation.), as well as (national, European, municipal) administrations and environmental protection agencies.

The decisions resulting from this type of LCA will lead to sector- or economy-wide changes.

Examples:

- A European Authority is drafting a new waste management plan for the next 10 years. The waste management plan shall include an analysis of the current waste management situation in the geographical entity concerned, as well as the measures necessary to improve its environmental performance. This should also include evaluation of how the new waste management plan will support the implementation of the objectives and provisions of the Waste Framework Directive.
- A nation-wide multi-system (i.e., parallel use of collection and treatment systems) study is being proposed for several waste flows. The main goal of the study is to establish priorities regarding the most relevant waste flows to tackle.

8.1.3 Accounting / Monitoring (Situation C)

8.1.3.1 General

Situation C typically concerns decision-perspective/retrospective accounting/documentation of what has happened (or will happen based on extrapolation forecasting) without accounting for any consequences that the target system may have on the background system or other systems. Situation C has two sub-types:

- C1 describes an existing system, but accounts for interactions with other systems (e.g., crediting avoided burdens from recycling);
- C2 describes an existing system in isolation without accounting for interaction with other systems (e.g., via substitution).

Note that Situation C2 rarely occurs in practice.

8.1.3.2 Situation C applied to waste management

Situation C applied to a waste management system should cover the following LCA applications:

Sub-type C1:

- Annual accounting of national waste management sector environmental impacts;
- Corporate or site environmental reporting including indirect effects under Environmental Management Systems (EMS);
- Development of specific, average or generic unit process or LCI data sets for use in Situation C1.

Sub-type C2:

- Accounting studies that according to their goal definition do not include interaction with other systems;
- Development of specific, average or generic unit process or life cycle inventory (LCI) data sets for use in situation C2.

Remarks

Situation C refers to annual accounting of environmental impacts from the national waste management sector. These annual environmental impacts shall include an analysis of the current waste management situation in the geographical entity concerned and all the related impacts on the environment. The model will also include the benefits of waste management, i.e., resources saved via recycling and energy recovery. This is done via substitution of the avoided burdens, i.e., Situation C1 is modelled identical to Situation A.

8.2 Minimum modelling requirements

8.2.1 Elemental and energy mass balance

When comparing waste management options with LCA, mass balances for the quantitatively / qualitatively most important chemical elements should be performed.

By example, the case of selective collection of plastic packaging will be considered here. If this stream does not contain metals, the residual stream will be relatively "enriched" in metals (e.g., metals from additives), with an effect on the impacts of the treatment of the residual fraction (metals emissions and recovery). The individual metals (such as aluminium and copper being mainly relevant as secondary resources, and cadmium being mainly relevant as toxic potential emission) are an example of qualitatively and quantitatively relevant elements.

Also, data from literature on composting and anaerobic digestion (AD) processes frequently refer to different waste streams, although both are biodegradable: inputs for AD are generally rich in food (kitchen) waste, while inputs for composting generally include more "green" (garden) waste. If composting and AD are compared to each other (to treat the same waste stream), the same amount of C, N, P and K should be found globally in the different outputs (atmospheric emissions, water pollution, the compost itself) because they have the same input materials. The same applies to the energy content of the waste and the various products and emissions resulting from the treatment.

If calculations are based on data of different origins, results may show a difference in the sum of all outputs of different treatment options. In this case, the comparison is not fair as the two options tackle different waste streams. Therefore, the LCA practitioner should model the distribution of those chemical elements among the output streams and adapt the data in order to get a coherent mass balance (sum of inputs = sum of outputs).

This modelling work is necessary to provide fair comparison between options. However, it is necessary to consider that both substitution and allocation of co-functions will alter this balance, i.e. the chemical and energy balance can only be performed on the level of the individual and entire unit processes. Such should also be part of a review of aggregated processes used as background data.

8.2.2 Non-proportional impacts

Inventory data of waste management processes from databases and publications refer to reference (typical, average, specific) waste compositions. But the real impacts of the process may vary disproportionally to the concentration of input materials. If this non-proportionality is major, with potential significant impacts on the results, a non-proportional model should be applied. Even if no models are published, simple models with a small number of assumptions can significantly improve the relevancy of the process data used in the LCA calculations (common-sense evaluation will produce better results than if these disproportion effects are ignored).

For example, about 85-90% of the steel present in bottom ash from incineration plants is extracted by the electro-magnetic extractor. The extraction efficiency is limited by the ratio between the weight of the steel piece and the weight of other materials contained in the bottom ash pile. The attraction force of the electro-magnet to the steel is proportional to the weight fraction of the steel fragments in the ash and the resistance is proportional to the total weight (ferrous + non-ferrous material). Therefore, small pieces (needles, nails…) are more difficult to extract (if they become dirty, the dirt weight might be significantly higher than the steel weight; also, even if not dirty, they might be placed under other waste preventing access to electro-magnetic extractor), while the real efficiency for large pieces is significantly higher. This means the selective collection of relatively large pieces of metals (e.g., cans) leads to lower extraction rate of residual metals from bottom ash; extraction of large steel pieces generally has an equivalency close to 1 for 1. Selective collection (of large steel fragments) would only provide a very small global increase of the recycled amount (global = selective + extracted from bottom ash). Conversely, selective collection of small pieces might significantly increase their recycling rate compared to magnetic recovery from bottom ash.

Another example of modelling non-proportional impacts occurs for transport (collection) discussed in chapters 9.3.2.2 and 9.3.2.3. Non-proportional impacts are not discussed further in this guidance for other waste management processes because LCA models for the specific processes do not yet exist or there application is not well established. In contrast, modelling the non-proportional impacts waste transport is a mature practice included in the majority of LCA studies pertaining to waste management.

It is therefore clear that (even simple) adequate modelling, coupled with sensitivity analysis, has a major added value and is highly recommended when non-proportional impacts are suspected and impacts on results and conclusions are potentially significant.

8.2.3 Interrupted operation

Process reliability can play a major role in an LCA; this is especially relevant to problems associated with waste preparation and with the process itself. If the process can be stopped and waste can accumulate/be stored to be treated later, this does not affect the LCA. Conversely, if waste cannot be stored (e.g., organic matter degrades spontaneously), an alternative process is necessary.

For example, bulking of an AD reactor may lead to a long-period shut down where waste must be managed using an alternative method, e.g., like disposal in a landfill.

Another type of interruption concerns the demand for output. This has different implications for the waste management system and for the user of the output/product. For example, heat recovery from a waste treatment process can only be effective when there is ongoing constant demand for heat or electricity generated by the recovery process. This is not the case if heat is used for house heating and heating demand is lower or interrupted at summer period. If there is no alternative demand, heat is lost at this period and the environmental benefits are reduced accordingly. In contrast, when heat is used for industrial operation (e.g., drying), the ongoing demand is almost constant (interruption is only limited to the interruption of the drying process).

If demand interruption happens regularly and there is no alternative valuable output, the modelled treatment should ideally be the weighted average of the base process and the alternative process.

8.3 Quality of the input data[68]

8.3.1 Overview

The quality of Life Cycle Inventory (LCI) data sets can be structured by representativeness (composed of technological, geographical, and time-related data), completeness (regarding impact category coverage in the inventory), precision / uncertainty (of the collected or modelled inventory data), and methodological appropriateness and consistency.

The ability of the inventory data to represent the environmental impacts of a system can be differentiated into two closely related aspects: representativeness and appropriateness[69].

Representativeness addresses how well the collected inventory data represents the "true" inventory of the process for which they are collected regarding technology, geography and time.

Appropriateness refers to the degree to which a process data set that is used in the system modelled actually represents the true process of the analysed system.

Following the identification of the most appropriate decision-context situation, data collection can start. Since the representativeness of the LCA input data is a key component of the overall LCA quality, the data collection phase needs to be carefully planned. As underlined in the ILCD Handbook "General guide for Life Cycle Assessment – Detailed guidance", Chapter 6.8 and 12, representativeness is classically evaluated from technological, geographical and time-related perspectives, which are closely interrelated.

[68] This refers to the ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance," Chapter 6.8 and 12 (Annex A), http://lct.jrc.ec.europa.eu/publications

[69] Note that here, same as in common LCA practice, both aspects are also jointly covered by the term "representativeness".

8.3.2 Technological representativeness

The technological representativeness of a process or system identifies how well the inventory data represent it with respect to its true technological or technical characteristics documented in the descriptive information of the data set or report.

An LCA can model:

- The average technology (to compare products using different technologies);
- The worst technology, practically applied to a relevant degree (to analyse its relevance of forbidding it, to stimulate investments or to import products from countries applying those old technologies);
- The best available technology (to develop a long-term vision).

8.3.3 Geographical representativeness

The geographical representativeness of a process or system identifies how well the inventory data represents its operating region (e.g., market, site(s), region, country).

For example, data for a specific treatment plant must rely on plant-specific operation data and not the as-designed or average operation conditions. Similarly, modelling the reduction of environmental impacts from substituting electricity with electricity produced from waste incineration should account for the national electricity mix (i.e., percentage of electricity generated by the various fuel sources such as coal, nuclear, hydro and wind).

8.3.4 Time representativeness

Modelling parameters (e.g., recycling rate, efficiency of energy recovery, emission limits) may change over time. Also, the best available technology (BAT) from 10 years ago may today be the average technology, or be already outdated; likewise, the average technology from 10 years ago may already be decommissioned or contribute only a small share to the current market mix.

Thus, the timeframe largely contributes to determine the relevant technology level. This is why both of the above-mentioned aspects (timeframe and technology level) are sometimes presented together.

Balance between technological, geographical and time representativeness

The flexibility to accept either a lower technological, geographical and/or time representativeness is largely influenced by the goal of the study. Data with good geographical and technological representativeness may be more appropriate in some instances than the most recent data (time-related representativeness). In addition to technological representativeness, geographical representativeness and time representativeness, other aspects influence the overall inventory data quality.

8.3.5 Sensitivity analysis

When representativeness and appropriateness of the data are not fully satisfactory, and results and conclusions are subject to change significantly if more adequate data were available, a sensitivity analysis should be conducted on those data.

Assumptions of “reasonably best” and “reasonably worst” cases should be made in comparison to the base case and/or main parameters and key processes and flows be varied and assessed in sensitivity analysis.

8.4 Type of required data and information[70]

During the initial scope definition and in preparation of the subsequent work, the main types and sources of data and relevant information should be identified. Expansion and modification of these data types and data sources will occur during the iterative steps of inventory data collection and modelling, impact assessment, and interpretation.

For an LCA, two types of data are required:

- **Inventory data on the process(es) of the system** (elementary, product and waste flows)
- **Parameters (process-operation and waste property information)** e.g., for an LCA on waste management, the following parameters would apply: waste composition and amount, collection distance, refuse rate, recycling rate, incineration rate, share of different technologies in a national waste management mix, etc.

The following data sources exist:

- **Inventory data:** A wide range of data exist:
    - <u>Primary data sources</u> are the producers of goods and operators of processes and services, as well as their associations. These data are typically compiled as primary data from the process/technology developer[71], goods producer, or process operator. Often, market average data are provided by business associations; these data are typically useful for the background system; e.g., LCI for plastics production developed by PlasticsEurope and LCI for steel production developed by the Worldsteel Association;
    - <u>Secondary data sources may provide</u> access to primary data (possibly after re-modelling / changing the data) or to generic data such as national databases, consultants, and research groups.

[70] This section refers to the ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 6.9, http://lct.jrc.ec.europa.eu/publications

[71] E.g., data on the use stage of consumer products. Other, independent sources may complement this.

- **Parameters (process-operation and waste property information):** the following list provides a non-exhaustive record of possible sources:
    - International organisations publishing statistics: United Nations, Eurostat, International Agencies, OECD, etc;
    - National statistics agencies;
    - Sectoral experts, stakeholder organisations, consultants and research institutions;
    - Scientific and technical articles in environmental books, journals and reports;
    - Surveys (municipal or other relevant administration, waste management companies, waste association organizations, other) and research projects.

Data must be collected from all waste management data sources and processes that have been identified. Ideally, the final model of the life cycle of any system would be represented only by process-specific data.

An actual collection/development of specific data is typically only required for the foreground system, provided all data in the background system can be sourced from available background databases. In practice, and as a general rule[72]:

- Specific data should be used wherever possible for foreground processes; only for data/processes that are not expected to have a significant influence on the results, secondary data or expert judgements and models (e.g., based on modelling from process knowledge) may be used instead. It is key that all low-quality data (i.e., “data estimate” quality level as defined in the ILCD Handbook – General Guide – Detailed guidance, chapter 12.3) are at least as good as required for the study performed to give reliable results. If this condition is not met, then specific data should be researched and included in a second model iteration;
- Generic or average secondary data may be used for background processes and also for the initial stage of modelling the foreground system, in order to identify the need for more representative or specific data.

[72] The foreground system consists of "the processes that are operated at the producer's facilities, but also all those processes at suppliers and downstream where only one or few operators are involved, i.e., where the specific processes cannot be replaced by market average supply data. "
The background system consists of "those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process." (cf. ILCD Handbook, p.97)

8.5 Selecting data on waste generation

8.5.1 Overview

Waste generation can be characterised by the following aspects:

- Source, e.g., households, small businesses, industrial plants, etc.;
- Amount generated;
- Composition (and other technical parameters that affect handling, storage, etc.).

Amount and composition of waste vary with population density, housing standards, climate and economic parameters such as household consumption or even cultural matters such as eating habits. For example, rural areas are likely to have greater amounts of vegetable, fruit and garden wastes than inner-city areas. Even within a given area, there will also be seasonal effects. Further, the composition and amount of waste generated will increase for holiday periods and the amount of garden waste increases in spring and summer.

Waste is generated from a variety of sources including households, offices, shops, markets, restaurants, public institutions, industrial installations, water works and sewage facilities, construction and demolition sites, and agricultural activities.

A good definition of waste composition is crucial to effective waste management and LCA modelling. For example, humidity will change the calorific value of bio-waste; the presence of additives, metals or other pollutants can affect flue gas cleaning (when burning) or hinder recycling, AD or composting.

The waste stream composition should be the same in all the waste treatment options being considered for comparison. For example, if W-t-E is compared to AD and composting either:

- the incinerated waste stream will be only the biodegradable fraction (i.e., with very small amounts of chlorine, sulphur, fluorine, metals etc.) and, therefore, generate low emissions of HCl, HF, SO_x, dioxins, metals, etc. and not using flue gas cleaning and corresponding reagents, water, electricity etc.) or
- the full household waste stream should be considered in both options and, as a complement to AD, a more contaminated fraction should be incinerated.

Particular care is needed to model the effect of selective collection on residual waste composition. For example, separating plastics reduces the heating value of the residual waste; separating bio-waste reduces the water content and, hence, increases the heating value, etc. As long as the real waste composition does not differ dramatically from the reference waste composition considered in the study providing secondary data), the effect of this change in waste composition on the treatment process should be modelled. On the other hand, in case composition changes so much that the former treatment process is not suitable anymore (e.g., too high or too low lower heating value LHV, heavy metals above thresholds for composting, etc.), a different treatment becomes necessary and the difference between the two treatment processes should be modelled.

Specific remark: In practice, launching selective collection of several streams does not lead to large changes in the treatment process of residual waste because opposite effects compensate each other. For example some selective waste steams have a high LHV (plastics, paper) but others have a low LHV (most bio-waste, glass, metals). Removing both streams for the residual waste may lead to a rather small evolution of the LHV of the residual waste.

8.5.2 Approach to data collection

Collection of inventory data for waste composition is defined by the scope of the study. There are different alternative approaches for collection of waste generation data:

- Collect <u>specific</u> data on generation of the waste from the geographical area under study, e.g.,
    1. For situation A: local/regional, site-specific data;
    2. For situation B: national or European data.

This enables development of unit processes that are specific for the waste stream in question. This approach is recommended. This will allow for calculations reflecting the extent to which changes in waste composition affect the LCA results.

If such data are not available or are of insufficient quality:

- Collect <u>specific</u> data on generation of the waste from a broader geographical level (e.g., for situation A: national or European data)*;*
- Collect <u>average</u> “default” waste generation data.

This enables development of unit processes that are average for the waste flow in question. Figure 13 provides guidance on how to approach data-collection on waste generation with respect to the decision-context situation A.

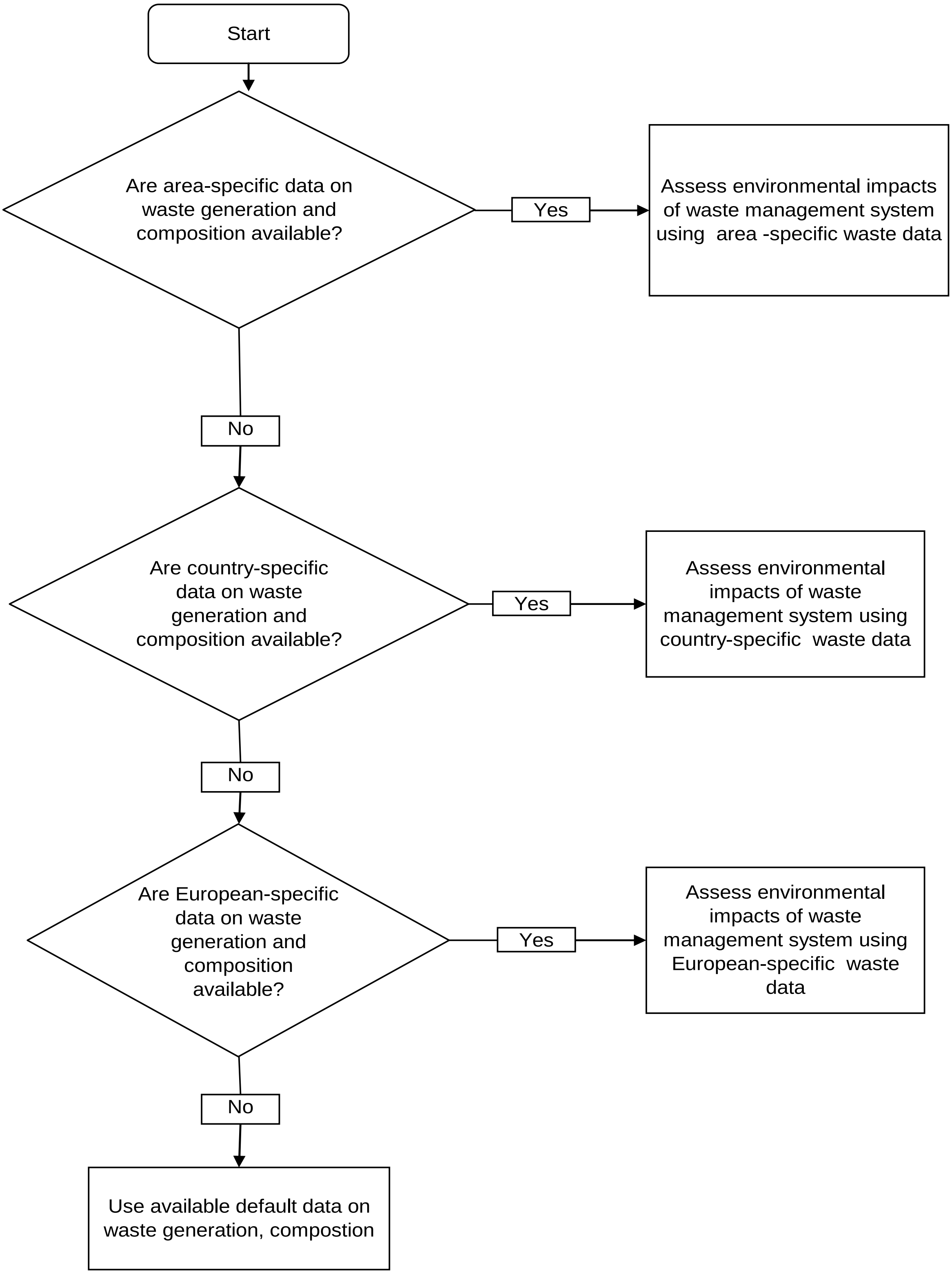


Figure 13: Decision tree – waste generation related data collection for Situation A

8.6 Selecting the type of inventory data

8.6.1 Overview

The approach chosen to collect/develop inventory data depends on the scope of the study and the availability of data.

The first approach to data collection identified in Chapter 8.5.2 (i.e., collect specific data on generation of the waste from the geographical area under study) may be used when a specific treatment process is compared to a fully integrated alternative. In all other cases, where waste composition varies, the second approach (i.e., collect specific data on generation of the waste from a broader geographical level) is preferable.

The optimum approach to minimise modelling errors is to combine some process-specific data (from the plants concerned in the area studied) with a model sensitive to waste composition. The following table summarizes the different approaches and their main characteristics.

Table 7: Different approaches to data development and collection

	Plant	Process inventory data	Waste composition	Geography	Situation
1.	One Plant - Specific	Direct measurement	Static - Specified	Plant Local	C
2.	Several Area - Specific	Direct measurement	Static - Specified	Local Regional National	C
3.	One or several	Model	Variable - Specific	Plant Local	A
4.	Several	Model	Variable - Specific	Regional National European	B

8.6.2 Process specific data

8.6.2.1 Single process data from one single plant

The most representative sources of data for specific processes come from measurements directly performed on the process, or obtained from operators by interviews or questionnaires.

Among others, the following types of directly or indirectly measured data and information can be differentiated for existing processes:

- Process- or plant-level consumption data;

- Bills and stock/inventory-changes of consumables;
- Emission measurements (concentrations plus corresponding off-gas and wastewater amounts);
- Composition of waste, especially the elementary composition and energy content in support of element and energy balances.

Next to measurements, it is typically helpful (also for cross-checks), or even necessary, (to fill gaps) to draw upon other data sources. Data in fact need scaling, aggregation or other forms of mathematical treatment to bring them in relation to the process' functional unit(s) and/or reference flow(s). These include:

- Patents;
- Process engineering models;
- Process specifications and testing reports;
- Legal limits;
- Data of similar processes/technologies/techniques;
- Best Available Technology (BAT) reference documents.

This approach may be recommended when the analyst knows that the waste is going to be treated in the particular plant where the data is derived from, or in a similar plant. However, one plant may receive waste from multiple sources (e.g., household, industry, etc.) and the derived data are related to multiple types of waste. This limits the direct relationship with the derived data and one specific waste stream (e.g., the household one). The LCA practitioners should make sure that either:

- The waste processed during measurement is the same (in for instance composition) as the waste defined in the functional unit; or
- Impacts of waste treatment are modelled taking into account the composition.

8.6.2.2 Average and generic process specific data from several plants/sites

This approach is recommended in studies with a broader geographical scope, for example, in national or regional studies. However, also for background data of micro-level studies for the background system such average or generic data will be used, including for substituting avoided burdens to account for benefits from recycling and energy recovery as electricity put into the national grid.

The selected plants should represent the variation in technology being used within the targeted geographical area.

For information and guidelines about the main different forms of process averaging please refer to the ILCD Handbook, General guide for Life Cycle Assessment –

Detailed guidance [73] Chapters 7.7. “Averaging LCI data” and 7.5 “Developing generic LCI data“.

8.6.3 Process and waste specific data

8.6.3.1 Single process data from one single plant

Inventory data are modelled as a function of waste composition and one single plant’s main characteristics (e.g., for an incineration plant: the specific energy recovery efficiency). Using those data requires modelling, based on specific data from the plant but also on all kinds of available data and information, including:

- Elementary flow dynamic models;
- Process specifications and testing reports;
- Patents;
- Lab data or pilot plant data;
- Data of existing, similar technologies / techniques;
- BAT reference documents;
- Legal emission limits.

This approach may be applied for system development purposes, where the effect of system changes on waste composition shall be quantified (e.g., the effect of introducing source separation of a material).

8.6.3.2 Average process data from several plants/sites

This approach may be applied for system development purposes with a broader geographical scope, for instance in case of national or regional studies, where the effect of system changes on waste composition shall be quantified.

For information and guidelines about the main different forms of process averaging please refer to ILCD Handbook Chapter 7.7 “Averaging LCI data”.

8.6.4 Waste specific data

The most representative sources of inventory data for average or generic waste specific processes come from databases, for instance:

- LCI databases (e.g., ILCD Data Network or the ELCD database[74]);

[73] http://lct.jrc.ec.europa.eu/assessment/projects
[74] http://lct.jrc.ec.europa.eu/assessment/data

- LCI waste management database or tool (for an overview see the LCA Resources Directory EPLCA[75]);

Among others the following data and information can typically be helpful (also for cross-checks):

- Patents;
- Legal limits;
- Data of similar processes/technologies/techniques;
- BAT (best available technology) reference documents.

The effort for collecting/developing inventory data sets is clearly smaller than in the previous approach but it has limited applications. This level of assessment can therefore only give a general perspective on the possible opportunities for improvement of the environmental performance of different management systems. It cannot be used to assess the performance of specific waste treatment systems or installations and cannot replace a thorough LCA.

This approach may be recommended when the analyst knows the target waste composition and it matches the waste composition used to set up the LCI from the database. If at least one composition is not known, LCI from database should be used with caution, i.e. for a first iteration of calculation, with thorough sensitivity analysis and/or with nuanced interpretation of the results. LCA practitioners should be particularly careful when the type of waste is clearly different, e.g., if available data concern an average for multiple waste types (e.g., household, industry, etc.) while the targeted waste is only one of those streams (e.g., household only).

8.7 Sensitivity analysis

When representativeness and appropriateness of data are not fully satisfactory and results and conclusions are subject to change significantly if more adequate data were available, a sensitivity analysis should be conducted on those data.

If sensitivity analysis needs to be applied to many data and modelling assumptions, combined sensitivity analysis should be performed, where different data change at the same time. If modelling with base data leads to the conclusion that waste treatment “X” is better for the environment than treatment “Y”, sensitivity analysis conducted for each input/parameter value one by one may lead to the conclusion that results are stable.

However, changing several values at the same time, forming cornerstone scenarios ("reasonably worst case scenario", “reasonably best case scenario”) could change the results significantly and even change conclusions. When conclusions based on different scenarios contradict each other, conclusions about environmental preference should be nuanced. If contradiction can result from poor data quality or

[75] http://lct.jrc.ec.europa.eu/assessment/

poor modelling, LCA practitioners should strive to improve data and models in order to get more relevant results.

This is why the stability of the results should be demonstrated by comparing a reasonable best case of treatment “Y” and worst case of treatment “X” (the best option, based on the base modelling). Note that "best" and "worst" cases relate only to realistic data and scenarios. For example, a prospective scenario for an option should not be compared to a current scenario for the other option because the comparison would not be fair.

9 Technical Guidelines for Life Cycle Based Modelling of Waste Management Processes

What is the focus of this chapter?

This section provides technical guidance on how to approach life cycle based modelling of waste management processes. These include waste prevention, collection, transport, re-use, recycling (and co-processing), energy recovery and landfilling.

Who should read it?

This chapter is mainly aimed at LCT/LCA practitioners who want to conduct an assessment related to waste management processes.

9.1 Prevention

9.1.1 Overview

9.1.1.1 Definition

The Waste Framework Directive (2008/98/EC) defines prevention as "*measures taken before a substance, material or product has become waste, which reduce:*

- *The quantity of waste, including through the re-use of products or the extension of the life span of products;*
- *The adverse impacts of the waste on the environment and human health;*
- *The content of harmful substances in materials and products*."

Examples include:

- Measures that can affect the design, production and distribution phases of the substance, material or product; and,
- Measures that can affect the consumption and use phases.

In the waste management context, prevention means checking the effects of policies on products in terms of reducing waste quantity and harmfulness. It is commonly stated that "*the best waste is the waste that does not exist,*" as resources are not lost and impacts associated with the production of the product and its waste management do not occur.

Two types of prevention measures can be distinguished:

- Prevention measures without upstream action, e.g., reducing food wastage by households. In this case, the environmental benefit is clear (saving agriculture, transformation, packaging, transport, meal preparation and end-of-life) and does not necessarily require quantification.
- Prevention measures with upstream action, i.e., ecodesign, which, for example:
    1. Reduce packaging weight, e.g., reducing weight of PET bottle;
    2. Promote reusability of product, e.g., using of reusable instead of one-way bottle. In this case, calculation of environmental benefits requires modelling of the full life cycle (i.e., including product manufacturing) for a fair comparison between both options;
    3. Extend the life span, e.g., making more durable products with modular construction (with potential replacement of outdated parts).

9.1.1.2 Requirements on enlargement of system boundaries

System boundaries:

- Should include all processes upstream of waste collection and treatment; whenever those processes are modified by preventive measures and enhancements that may affect the assessment of prevention measures (e.g., if a chip is added to a product in order to allow for a perfect automatic waste sorting, the production and end-of-life of the chip should be included in the waste management LCA study);
- May exclude upstream processes when it is justified, i.e., either because the processes are not affected by the preventive measures or because the changes are negligible and do not significantly affect the results, e.g., the redesign of a washing machine to use less material will not affect the way it is used by consumers; hence, the use phase may be excluded from the modelling.

9.1.2 Key technical and modelling aspects

9.1.2.1 Diffusion of preventive measures

Calculating the environmental impacts of a preventive measure requires determining the amount of waste saved. The latter corresponds to the multiplication of the intrinsic potential (kg/unit) by the target number of units in the study area. This number depends on the number of persons/producers who actually make the prevention action. This might be reflected in the so-called diffusion factor (F_D), i.e., the percentage of population/producers that effectively changes its consumption behaviour as a consequence of the prevention policy.

The waste reduction potential may be quantified through solid waste component analysis.

9.1.2.2 Indirect effects

Prevention measures can affect other life cycle steps (i.e., the production, distribution, consumption, and use phases). Therefore, calculating the environmental impacts of a preventive measure requires including all processes upstream of waste collection. Two modelling approaches are possible:

- Integral approach: modelling the whole life cycle with and without the prevention measures and comparing both results;
- Differential approach: modelling only the differences, using the situation without the preventive measure as a reference.

Both approaches lead to the same differences between the systems. The difference lies in the ease of interpretation:

- The first approach clearly shows the relative importance of the prevention measure within the full life cycle; this is helpful to set up priorities;
- The second approach is less work intensive (some processes are left out) and focuses on the differences, ideal for optimising processes as results are more sensible. However, the risk of leaving out processes affected by prevention is greater than with the first approach.

The calculation requires determining the environmental impact of:

- The avoided production of the material that becomes waste. This is generally the major avoided impact;
- The avoided or additional upstream life cycle stages that are affected by the prevention measure, such as distribution and use. For the distribution phase, two situations can occur (see detailed discussion in Chapter 9.2.2):
    - o The prevention measure does not change the amount of goods that can be transported in one vehicle (e.g., volume is the limiting factor and the volume of the goods is not affected by the measure). The (very small) benefit regarding the distribution phase is the avoided

consumption due to weight of the avoided material (same number of km but lower fuel consumption per km of transport);

- o The prevention measure allows increasing the amount of goods than can be transported in one vehicle (weight is limiting factor). The benefit of this measure regarding the distribution phase is to reduce the amount of vehicles per functional unit. This leads to higher benefits than the first situation.

- The avoided waste management.

Figure 14 illustrates an example of the system to be modelled for assessing – using the differential approach – the environmental impacts of a prevention measure that consists of reducing the amount of steel in a washing machine by 1 kg. All other parameters remain unchanged (volume, energy consumption, etc.). In this example, 85% of the steel from discarded machines is recycled.

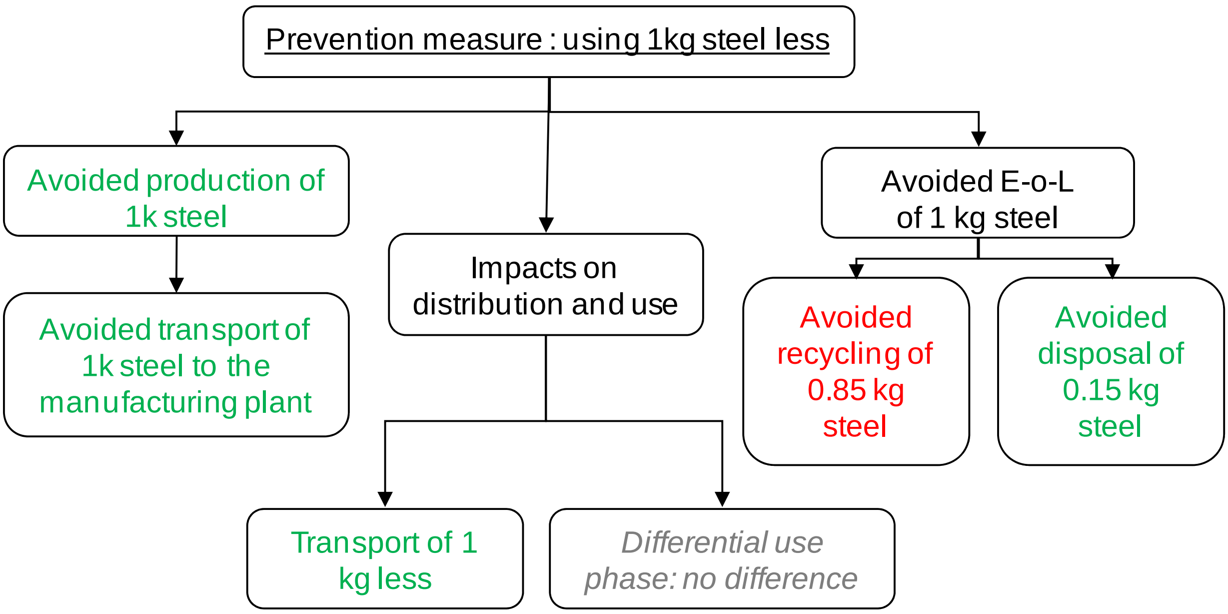


Figure 14: Example of prevention: Reducing the use of steel by 1 kg in a washing machine (differential modelling). Key: Green = less impact / Red = more impact / Grey = 0 impact

9.1.3 Modelling recommendations

- The system boundaries should include all stages that could be modified by the prevention action (including alternative production, transformation, transport, storage and, of course, waste management). The procedure of identifying possible effects might be quite time consuming but is worth doing because it can significantly influence the model results;
- Concerning waste management, specific modelling is necessary. For example, a lighter bottle might take the same volume in the waste-bin and the waste collection truck. This means that weight reduction (and, thus, waste reduction) does not reduce the impacts at collection stage. LCA practitioners should avoid calculating LCI for transport as a multiplication of the weight by an LCI per kg of waste. Transportation/collection impacts are generally proportional to the waste volume rather than to its weight.

9.2 Collection

9.2.1 Overview

Waste collection refers to the situation where waste is distributed over a given area and needs to be gathered (typical stop-and-go driving mode) before being sent to a treatment or storage facility. The collection stage ends at the first unloading site. Typically, household waste always needs to be collected.

The overall environmental performance of collection varies greatly and results from specific performance in terms of collection frequency, emission levels, amount and type of fuel, etc. These specific values depend on:

- The characteristics of the collection vehicles: technology (type of fuel, particle filter, emission category, e.g., Euro 2, Euro 3, etc.);
- Operation: frequency, driving practice, vehicle maintenance, collection mode (bring system, e.g., central collection site, low/high density of materials banks at street-corner container, or curbside collection), etc.;
- Transport distance and population density: low, high, intermediate;
- Waste composition: raw waste, light packaging, glass, etc.;

In the case of mixed collection, the truck impacts need to be allocated among the different waste streams.

Indirect effects of collection need to be considered:

- When a selective collection is added, the waste collected selectively is no longer collected together with the mixed waste. This saved collection needs to be modelled for the mixed waste.

- Impacts generated by cars queuing behind additional trucks.

9.2.2 Key technical and modelling aspects

9.2.2.1 Allocation

Curbside collection system

Since an LCA frequently focuses on only one of the waste types being collected within a mixed waste (e.g., organic waste in mixed waste, cans in a packaging stream…), a question arises: “How shall the impacts of waste collection be allocated between different waste streams collected together?".

The most relevant basis for allocation is a physical relationship: when does the truck need to be unloaded? This requires identifying the limiting factor to lower the number of km per tonne of waste collected. Most of the time the filling characteristic that is reached first in the truck is either weight (maximum load is reached while the truck is not full yet) or volume (no space in the truck anymore).

Sometimes the limiting factor is the comfort of waste producers (e.g., the citizens) and the collection frequency is set up as to avoid storage over a long time period. This might often be the case for biodegradable waste from households or bulky waste from shops in cities. In this case, the truck does not get filled up to its capacity and the collection trip is, thus, not optimised. The increased impacts from the collection phase should then be allocated to the waste stream requiring the high collection frequency.

Bring collection system

Two allocation issues arise for this type of collection system when people bring waste to the waste collection place with their car (van).

Bringing waste to a collection point is often part of a multi-stops trip (e.g., going to work, going shopping, going to school, etc.). Thus, only a part of the trip should be allocated to bringing waste to the collection point. Possible allocations methods are:

- Allocate only the additional distance compared to the same trip without going to the waste collection place (typically when it is included in a "regular" trip, e.g., on the way to or from work, school, etc.);
- Allocate only the one-way-trip from home to the collection place (and not the trip to the other destination);
- Allocate according to the number of destinations (e.g., if there are 3 destinations, 1/3 of the full trip is allocated to bringing waste).

When this stage is crucial for the LCA results, a field survey might be required to select the most relevant method. Based on the survey, different profiles may appear, leading to different allocation methods being applied to different (types of) users. For instance, people bringing a lot of waste often make dedicated trips, while people bringing small amounts preferably do it on their way to/from another destination.

When waste owners make a dedicated trip to the collection site, then, obviously, the full trip is allocated to bringing waste to the collection point.

When several waste streams are transported together, the trip must be allocated among them. Possible allocations methods are:

- Allocate according to the waste volume, either because the need to evacuate waste was determined by the volume taken at home or because the car is full of waste. This should be the base case (default allocation method);
- Allocate to the waste stream creating a specific need for collection (e.g., odorous organic waste, full paper box, a lot of glass bottles after a party, a lot of demolition waste, etc.).

9.2.2.2 Influence on other waste management steps

Given the interdependence between the collection stage and other stages of a waste management system, it is important to assess the influence of collection schemes on the subsequent steps of waste management. Collection characteristics mainly affect:

- Degradation state of waste: If the collection frequency is insufficient, partial degradation of biodegradable waste may lead to toxic atmospheric emissions or emissions contributing to the greenhouse effect. Those emissions can be liberated at the storage place or the gases generated may remain captured within the waste (bag) and be liberated later, during collection and/or discharge, at the treatment place and/or during the treatment itself (e.g., in the case of composting);
- Effective recycling rates: Collection method can influence the quantity and/or quality of recovered materials;
- Quantity: this directly affects the amount of material recycled. For instance, a deposit system (e.g., for bottles) may increase the environmental impacts from collection (crushed bottles use less volume, longer return trip) but also lead to an increase in the amount of material collected and recycled, possibly moving the environmental benefits balance in favour of the deposit system compared to the selective collection system;
- The quality of the collected material determines whether markets can be found and affects the efficiency of the recycling process. For example, selective selection collection schemes dedicated to a single material may yield higher effective recycling rates than mixed collection.

All those factors should be analysed when optimising waste collection. The accuracy of the results depends on the correctness of this analysis. When the LCA study applies to several complete waste management systems, those influences will be automatically considered in modelling the other waste management stages.

9.2.2.3 Modelling the impacts of collection vehicles

The specific fuel consumption of a waste collection vehicle varies according to the load weight. Moreover, the load weight varies according to the waste density. Therefore, a specific modelling that employs system specific load densities is preferable to using standard values expressed in tonne*km that provide indicative values, ignoring the sensitive effect of density.

In most cases, impacts from infrastructure (truck and road construction and maintenance) are relatively small compared to the impacts linked to the use phase (fuel consumption and related production and atmospheric emissions). This does not imply infrastructure may systematically be neglected, but often it can be concluded that a rough modelling is sufficient. For example, the system boundaries could include the production of the materials (and end-of-life) but exclude transformation, transportation and construction (and end-of-life) of the infrastructure.

The impacts of collecting 1 tonne of waste over a distance of X km with a waste collection vehicle may be calculated as follows:

Equation 1

$$^{1\ \text{tonne}}/_{\text{real payload}} * \text{LCI} * \text{X (km)} * \text{Y}$$

With

- LCI = the LCI of driving 1 km with a waste collection vehicle, in a trip where the truck gets fully loaded (based on a 70-100 litres diesel per 100 km)
- Y = 2/3 + 1/3 * LR; this reflects the fact that the consumption of an empty truck is about 2/3 of the consumption of a fully loaded trucks[76]; for a fully loaded truck, Y = 1
- LR is the loading rate; LR = real payload/maximum payload

[76] The EcoTransIT “Environmental Methodology and Data - May 2003” states that: "The influence of the load factor is modelled according to the differentiated values in the Handbook of Emission Factors. Accordingly, the fuel consumption of an empty vehicle can be 1/3 below the fuel consumption of the fully loaded vehicle."

- Real payload = amount of waste transported per vehicle when it has to stop either because it is full (no space) or because the maximum weight is attained, e.g., for light waste (e.g., plastics), the limitation factor is volume, while for heavy waste (e.g., glass), the limitation factor is weight. As waste is compacted in the waste collection vehicle, the compacted waste density should be used to determine the limiting factor.

If the LCI refers to a fully loaded vehicle (but this is rarely the case), Y = 2/3 + 1/3 * 50% * LR because, on average, the vehicle is half-loaded.

The modelling can be further refined when collection is a key stage, considering separate LCIs:

- For driving (from garage to first collection point, from last collection point to unloading point and from unloading point to garage or back to the first collection point of a second trip in a day), with a consumption of about 30-40 litres per 100 km;
- For collection itself (loading, with lots of starts/stops), with a consumption of about 100 litres per 100 km.

Remarks:

- Fuel consumption of waste collection vehicles is higher than for conventional trucks because of their additional equipment (for crushing waste) and their stop-and-go driving mode. Therefore, LCI of collection vehicles cannot be approximated using fuel consumption for conventional trucks;
- Since a collection vehicle journey is relatively long, cold-motor emissions are negligible.

9.2.2.4 Modelling the impacts of cars

Little data are available in the literature about the distance covered by individuals bringing waste to collection points. Therefore, sensitivity analysis is required when this stage appears to generate significant impacts.

Key points in case of modelling:

- Fuel consumption may be assumed to be independent of the waste load, because the weight of the waste is generally small compared to car weight;
- Because the trip to the waste collect point is generally quite short, cold motor emissions and fuel consumption should be considered for the 2 first km. As default data, doubling consumption and emissions can be considered. If this appears to have a significant impact on the results, more specific data should be gathered and/or sensitivity analysis should be performed;
- Allocating fuel emissions to recycling based on the reason for the journey (e.g., if individual was also driving to work or to shops).

9.2.3 Modelling recommendations

9.2.3.1 Pre-assess the relative importance of the collection stage

This stage often appears to generate only a small fraction of the environmental impacts and benefits. In this case, a simplified modelling can be applied (LCI per tonne * km * # tonne * # km).

Otherwise, either a sensitivity analysis or (preferably) a more sophisticated modelling is required, considering cold start, variable speed in different trips, allocation, waste density, etc. LCA practitioners should also include fuel production and infrastructure.

9.2.3.2 Consider alternatives

For urban waste collection, pneumatic collection may be regarded as a valuable alternative (see "LCA of selective waste collection systems in dense urban areas”[77]) to traditional collection (curbside or bring). The modelling should consider:

- Energy consumption for operation of the pneumatic conveying, considering the number of hours per week the system is operated;
- Manufacture and installation of pipes.

9.3 Transport

9.3.1 Overview

We refer to transport when the waste to be moved is located at one collection point. Waste transport is the movement between that location and the final destination. For instance, after collection of household waste, additional transport is needed between the sorting facility and treatment facility. Waste transport differs from waste collection because it has only one collection point and consumes therefore much less fuel per km.

9.3.1.1 Key parameters

The overall environmental impacts of transport depend on:

- Transport distance;

[77] LCA of selective collection systems in dense urban areas; A. Iriarte et al., Waste Management 29 (2009)

- Vehicle characteristics: Transport mode (truck, train, barge, tanker, plane, etc.); Compliance with emission limits: EURO norm (EURO 3, 4, 5); Fuel consumption and type of fuel (for trains, the type of energy source, i.e., electricity or diesel, is also an important parameter);
- Operation: driving practice (speed, etc.), vehicle maintenance;
- Waste density.

9.3.1.2 Definitions

There are several definitions for truck weight. These should be clearly specified in order to avoid confusion:

- Tare weight: weight of the empty vehicle (unloaded). A tare weight is defined separately for the tractor and the trailer (if present);
- Total authorised loaded weight (TALW): This is the maximum weight a truck or trailer may have, inclusive of its load. It is therefore specific to each part of the whole truck (tractor and trailer), as is the tare weight;
- Gross combination weight (GCW): This is only defined for semi-trucks and tractors (i.e., only for vehicles with the capacity to tow). It is the maximum weight of the whole truck (tractor + all the trailers);
- Gross vehicle weight (GVW) = GCW + load: This does not apply to a part (truck, trailer, etc.) but to the whole vehicle. It is prohibited to load a truck so that its weight exceeds the GVW. For trucks with no trailer (truck in one piece), the GVW is equal to the TALW. This is the most frequent case;
- Maximum Payload: This corresponds to the maximum load the whole truck-trailer may transport;
- Load limiting factor: characteristic of a truck that impedes further loading of the truck. In practice it is either the weight (max payload is reached) or the volume (the truck is full); seldom it is the surface (e.g., for light, fragile load, when pallets cannot be put one on the other).

9.3.2 Key technical and modelling aspects

9.3.2.1 Allocation

The limiting factor is the filling characteristic that is reached first. This limiting factor must be identified in order to calculate the real payload of the truck (as used in the previous section). Two situations can be distinguished:

- <u>Weight is the limiting factor</u>

If waste is dense, the load weight generally limits the amount of waste that can/may be transported in a truck. Indeed, the maximum allowed weight is reached before the loading surface of the truck is physically full. In this case, the allocation between waste streams should proportional to their "weight".

- Volume (surface) is the limiting factor

For less dense waste, trucks (or other transport modes) can be fully loaded without reaching the maximum payload. In this case, the available volume (surface) limits the amount of waste transported per trip. The allocation between waste streams should be proportional to their "volume".

If several waste types are collected together, each waste type can be modelled as if collected separately, using the real payload of the truck based on the limitation factor of that particular waste type.

9.3.2.2 Modelling transport by truck

As discussed elsewhere, the specific fuel consumption of a truck varies according to the load and the load varies according to the waste density. Therefore, a specific modelling should be preferred above standard values expressed in tonne*km that provide only indicative values ignoring the sensitive effect of waste density and of the variable distance to drive empty in order to get to the loading place. The impacts of transporting 1 tonne of waste over a distance of X km with a waste transportation vehicle may be calculated as follows:

Equation 2

$$^{1\ \text{tonne}}/_{\text{real payload}} * \text{LCI} * \text{X (km)} * \text{Z}$$

With

- LCI = the LCI of driving 1 km with a fully loaded truck (based on a 30-40 litres diesel per 100 km), variable as a function of EURO norm (EURO 3, 4, 5), maximum payload, specific fuel consumption, type of fuel (the most widely used fuel for heavy trucks is diesel, but there is also gas or biogas)
- Z[78] = (2/3 + 1/3*LR) + ERR * 2/3; this reflects the fact that the consumption of an empty truck is about 2/3 of the consumption of a fully loaded truck[79] and the need to drive empty to the next loading place;
- LR is the loading rate; LR = real payload/maximum payload
- Real payload = maximum amount of waste transported per vehicle. This maximum is due to either full space occupation or to reaching maximum weight (see 9.2.2.3).

[78] EcoTransIT “Environmental Methodology and Data - May 2003” states that: "The influence of the load factor is modelled according to the differentiated values in the Handbook of Emission Factors. Accordingly, the fuel consumption of an empty vehicle can be 1/3 below the fuel consumption of the fully loaded vehicle."

[79] The EcoTransIT “Environmental Methodology and Data - May 2003” states that: "The influence of the load factor is modelled according to the differentiated values in the Handbook of Emission Factors. Accordingly, the fuel consumption of an empty vehicle can be 1/3 below the fuel consumption of the fully loaded vehicle."

- ERR = Empty Return Rate = $^{\text{distance empty}} / _{\text{distance loaded}}$ = distance driven by the empty vehicle after unloading to the new loading place divided by the distance driven with the initial load.

Examples of Empty Return Rate (ERR)

Example 1: an ERR of 20% means that when a truck travels 100 km to deliver its load, it will travel an extra 20 km to get a new load. This extra distance is allocated to the delivery of the first load.

Example 2: If the truck only delivers the waste from the factory to the waste treatment plant and then comes back empty to the factory, the ERR is 100% and a full return trip is allocated to the waste transport.

Example 3: There can also be negative ERR. This occurs when the transported material takes advantage of a journey that would have taken place anyway. This material hence has an ERR of -100%. Only the emissions due to its weight in the vehicle have to be accounted for (the emissions from the vehicle itself are allocated to the product responsible for the journey; this product hence has an ERR of 100%). More generally, when considering two identical trips in opposite directions over long distances (like tankers), their respective ERR values are opposite (or are both 0).

9.3.2.3 Modelling other transports

Unless transport appears to be negligible, specific modelling should be preferred above standard values expressed in tonne*km that provide only indicative values. The models should consider:

- The variable fuel consumption as a function of the load and of the type of motor;
- The type of fuel (or the way electricity is produced for electric trains, which is a crucial parameter);
- The ERR.

Remarks:

- Train LCIs are generally given in tonne*km, leaving little leeway for specific modelling. However, loading rates and ERR are usually not easy to obtain for trains, making the availability of default values very useful;
- For oceanic transport, an interesting case needs to be discussed: the imbalance between transport from Asia to Europe and the return journey (see example 3 above). Demand for transport is much higher from Asia to Europe. Ships frequently go back from Europe to Asia empty. The products imported from Asia hence have an ERR of 100% (i.e. the whole trip back to Asia is allocated to their environmental profile). Waste that is sent from Europe to Asia then has an ERR of -100%. Only the consumption due to the weight of the waste in the ship for the trip from Europe to Asia needs to be considered.

9.3.3 Modelling recommendations

9.3.3.1 Pre-assess the relative importance of the transport stage

This stage frequently appears to generate only a small fraction of the environmental impacts and benefits. In this case, a simplified modelling can be applied (LCI per tonne * km * # tonne * # km).

Otherwise, either a sensitivity analysis or (preferably) a more sophisticated modelling is required, considering allocation, waste density, etc. (see Chapter 9.3.2.2). LCA practitioners should also include fuel production and infrastructure within the system boundaries.

9.3.3.2 Analyse the Empty Return Rate (ERR)

When transport is not negligible, the modelling should carefully consider the ERR, especially when there is a great imbalance (e.g., ships Asia-Europe and return).

9.3.3.3 Include and discuss qualitative impacts

LCA practitioners should consider inclusion of non-standard impacts and elementary flows such as noise, congestion and accidents. However, there are no standard databases and methodologies for including these issues. Therefore, those elements should be discussed based on limited quantitative data and, more frequently, qualitative data. Those elements should also be considered in the conclusions.

9.4 Re-use

9.4.1 Overview

The Waste Framework Directive (2008/98/EC) defines

- re-use as "*any operation by which products or components that are not waste are used again for the same purpose for which they were conceived*."
- "preparing for re-use" as "*checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing*"

Re-use allows extending the lifetime of an object when it comes to the end of its useful lifetime for its first owner. Re-use is, therefore, a way of waste prevention. Some operations can be carried out to extend the object lifetime but its nature or use remains unchanged. Re-use options do not include reusable objects as opposed to disposables, as this is considered as prevention.

Note: Re-use of a refillable (re-usable) bottle is not waste re-use as the bottle has not been waste.

This is a particular area of waste management where the frontier between product and waste is not always clear.

9.4.2 Key technical and modelling aspects

9.4.2.1 System boundaries

Re-use generates environmental impacts by increasing the use phase of a given object while avoiding the impacts from producing, using and disposing of an equivalent new object. This can be modelled in two ways. The production, use and end-of-life of the new product can be:

- Added to the alternative system;
- Subtracted from the re-use system (as avoided impacts).

Both modelling options lead to the same relative results between the re-use system and the alternative system.

9.4.2.2 Saved processes

When reusing a product, the saved end-of-life is not the one of the re-used product (it will become waste again anyway) but the end-of-life of the new product. For example, if a steel product in re-used instead of using a new product in aluminium, the saved end-of-life is the end-of-life of aluminium.

Additional function: No product replacement

In some cases, the re-used products do not replace new products. Indeed, as re-used products are generally cheaper, they become accessible for low-income households that could not have afforded to buy this product new. In this situation, re-use does not avoid the production, use and end-of-life of a new product, but rather creates additional impacts (in the case of products that use consumables).

In such situations, an additional function of re-use is to create access to these products for low-income households. Unless this function is also added to the alternative system, fair environmental comparisons cannot be made.

9.4.2.3 Lifespan

One of the key parameters for modelling re-use is the lifespan of the "re-used" object and of the equivalent new object. This parameter is important for two reasons:

- *The share of the new object that is avoided (production and end-of-life)*. Indeed, the re-used object does not *per se* avoid 100% of the new product.

For example, if a product is usually used for 5 years, re-use actions can extend its lifetime to 7 years. The new product will be avoided for 2 years, which represents 2/7 of its lifetime. Hence, production and waste are reduced by 2/7.

- *Calculation of impacts during the use phase*. This calculation is highly dependent on the duration of the use phase (which is the same for both the re-use and the alternative systems). The calculation also depends on the technology improvement rate, as explained below.

9.4.2.4 Relative importance of life cycle stages

The refurbishment stage is specific to the re-use system. This stage generates relatively small environmental impacts that are generally negligible compared to the other life cycle stages.

With respect to products that use consumables, the use phase is generally the key stage for the comparison. A key parameter for modelling re-use is, therefore, the technology improvement rate.

Re-used equipment does not benefit from technology developments, which generally improve efficiency. Considering the same example as above, the average lifespan of the re-used product is 6 years (=(5+7)/2) and that of the new product is 2.5 years (=5/2). Statistically, re-use increases the average lifespan of the product by 3.5 years, hence, it loses the benefits of 3.5 years of technology improvement. The consumption rates are thus different for the re-used and the new product, with the new product generally generating less environmental impacts, like consuming less energy, water, etc.

9.4.2.5 Modelling the number of uses including the initial stock

Re-use is not only a product product/system design issue *sensu stricto*, but it can also be integrated into the waste management policy in order to prevent waste generation.

Two main categories can be distinguished:

- Reusable with a stock (e.g., packaging with a return and refill system; when launching the packaging, an initial stock needs to be produced)
- Reusable without a stock (e.g., nappies).

The modelling principles are the same for both categories except for the calculation of the number of uses, which is more complex in the case of a reusable product with a stock (cf. box below).

When the objective of an LCA is to compare a reusable product with its disposable counterpart:

- The differential approach – as applied above – cannot be applied, as the systems are too different;
- Life cycle stages that are the same for both systems can still be left out of the boundaries;
- The functional unit cannot be expressed in terms of the product itself but must be expressed in terms of the function fulfilled by the product e.g., when comparing reusable versus disposable beverage packaging, the functional unit will be expressed in terms of the amount of beverage contained and not about the packaging itself.

The essential parameter for LCA of reusable products is the number of times the product is used (including the stock, when applicable). Indeed, because of losses and the physical properties of the products, reusable products can actually be re-used only a limited number of times. Marketing reasons or consumer demand also influence the lifetime of reusable products. Depending on the product, the "number of uses" parameter is not always easy to obtain but may have significant impacts on the results of the LCA. Where there is uncertainty, sensitivity analysis should be performed.

The differences between the modelling of the reusable system and the disposable system are:

- Non-recurrent processes are divided by the number of uses, i.e. production and end-of-life of the reusable product;
- Additional life cycle stages associated with re-use, mainly return transport and washing. These stages do not apply to all products, but only to products that are returned.

When analysing re-use systems where products (packaging) are conceived for several uses (e.g., refillable vessels or bottles), modelling the number of uses should include both:

- The number of uses including the initial stock;
- The replacement of damaged products by new ones.

The analysis should be made over the complete economic lifetime of the product on the market. So, the number of uses should be calculated as:

Total production of bottles = Initial number of bottles + number of new bottles per year * years of existence of the system

Total number of uses = number of uses per year * years of existence of the system

Equation 3

$$\text{Average number of uses} = {}^{\text{Total number of uses}} / {}_{\text{Total production of bottles}}$$

9.4.3 Modelling recommendations

The main recommendations are:

- Calculate the number of uses applying the formula given in 9.4.2.5;
- Pay careful attention to the modelling of the saved end-of-life (the end-of-life of the new product is saved, not the end-of-life of the old product);
- Consider realistic evolution of performance for products consuming energy, water, detergents, etc. The characteristics of buyers of re-used products (low-income in general) means in general the replaced new equipment would be among the cheapest and, therefore, the least efficient (although correlation between cost and performance is far from perfect);

- For reusable without a stock, re-use means making the use phase longer. Re-use is **not** intended at the design phase of the product. The number (fraction) of saved products is equal to the ratio between the duration of the second life and the duration of a new product.

  For example:

  - For an object (e.g., tableware), the life durations will probably be the same (until it is lost or broken or discarded) and the ratio = 1;
  - For equipment (e.g., computer), the second life will often be shorter (because it becomes outdated or degrades) and the ratio < 1;
  - For a quality degradable object (e.g., cloth, bicycle), the second life may even be longer (because its intrinsic quality is better) and the ratio > 1;
- For reusable with a stock, re-use is intended at the design phase of the product. As stated in "Annex C (Modelling re-use, recycling, and energy recovery)" of ILCD Handbook General guide for Life Cycle Assessment – Detailed guidance[80], "*Methodologically, all the different forms of re-use, recycling, and recovery of energy are equivalent in LCA. This covers, reprocessing of production waste, regeneration of nuclear fuels, restoration of buildings, reclaiming or recovering energy, reusing and further using parts or goods, refitting parts for other goods, repair, rehash, etc*." The modelling should be as follows:
  - Non-recurrent processes are divided by the number of uses, i.e,. production and end-of-life of the reusable product;
  - Additional life cycle stages associated with re-use, i.e. generally return transport and washing are considered. (Note: These stages do not apply to all products, but only to products that are returned).

[80] http://lct.jrc.ec.europa.eu/assessment/projects

9.5 Recycling

9.5.1 Overview

Calculating the environmental impacts and benefits of recycling in an LCA can be a complex task. The key question concerns the benefits of avoiding using another "virgin" material:

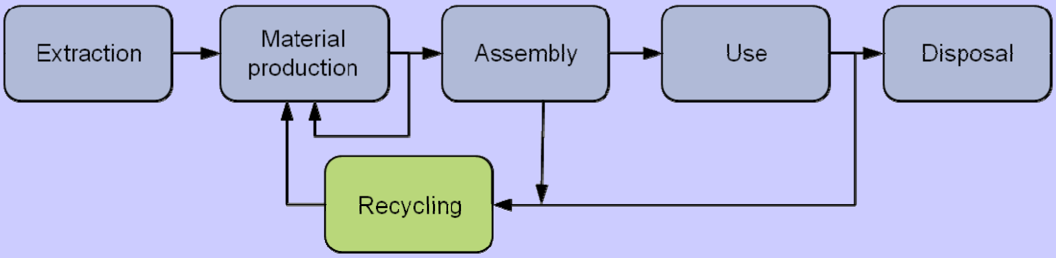
- Which primary material is saved? (e.g., does recycled HDPE replace virgin HDPE, PP or PET, or even glass or another material?);
- How much primary material is saved? (In some cases, the product made with the recycled material is thicker and heavier in order to achieve the same mechanical properties; therefore, more recycled material is used per product unit compared to the virgin product);
- Which production process is concerned?

The amount of energy needed to transport, store, and re-process waste into the secondary material also needs to be considered but the way it is modelled is in general much less crucial.

A key concept in the modelling of the recycling system is the definition of closed-loop and open-loop recycling. The ILCD Handbook, General guide for Life Cycle Assessment – Detailed guidance [81] defines them as follows:

Closed-loop recycling

The simplest form of recycling is closed-loop recycling. A secondary good is passed back to an earlier process in the same system (e.g., recycling of gypsum from waste plasterboard back into new plasterboard). It directly replaces ("substitutes", or "supersedes") input from primary production of the same material.



In this case, accounting for benefits is relatively simple. A reduced amount of primary ("virgin") material is needed to produce the product, reducing overall impacts. The primary material savings can be evaluated based on current recyclability rates achieved (see overleaf).

The need to dispose of the waste material by other means is also avoided. And don"t forget that the impact of transporting and processing the secondary ("recycled") material will need to be added. In some cases, this can be an important step, and is one that should not be

[81] ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance," Chapters 14.3 to 14.5, http://lct.jrc.ec.europa.eu/publications

overlooked.

Open-loop recycling

A more common form of recycling is open-loop recycling, where at least a share of the secondary material is used for a different purpose than the original. This includes materials that are recycled into the same type of material, but are used for different products. For example, steel from a building-site is recycled to produce other steel products. In this case, the secondary material (steel) and the primary material it displaces (steel) are inherently the same.

Open-loop recycling also includes materials that are recycled into secondary products that have different properties and inherent uses. For example, gypsum in plasterboard being recycled for use in compost, recycling plastic into street furniture, replacing wood, or integration of minerals from waste raw materials into the cement clinker matrix by co-processing is fulfilling the criteria of recycling”. In these cases, the primary material that is being displaced is entirely different.

In some cases of “open-loop recycling” (see box below) – where there are no changes to the inherent properties (e.g., many metals) – recycling benefits can also be accounted for in the same way and treated as a closed loop.

9.5.2 Key technical and modelling aspects

9.5.2.1 Substitution – quantifying the benefits of recycling

Substitution is a common approach used in quantifying the benefits of open-loop recycling and is applicable in many situations. The “avoided” production of a primary material is credited to the waste stream according to how much primary material is saved. The impacts of transporting, re-processing the waste and disposing of any non-recyclable material must also be considered.

It is important to consider the following points:

- **Recyclability (measured as achieved recycling rate[82])**. The “recyclability” of a waste material is not just the amount that is collected for recycling – it is the amount (%) of material that actually ends up as a secondary product. It account for all losses across the collection, sorting and recycling chain. Note that for products made up of many materials or component parts, the “recyclability” of each material needs to be considered separately. The amount of recyclable and actually recycled materials, and where, when and how this recycling is achieved should be clearly documented in all LCA studies;

[82]Note that there are different definitions for the term “recycling rate”, used by different groups and in different contexts. It is important is to be clear about the meaning in each instance. Refer to the ILCD for a full definition of terms.

- **Changes in inherent technical properties ("down-cycling").** The technical properties of a material may sometimes become degraded during a recycling process. For example, fibres are shortened/smoothed during paper recycling, and plastics may lose some aesthetic (colour) and mechanical/chemical qualities as different colours, grades, and types of plastic and additives plastics are recycled together (imperfect separation by the collection/sorting/recycling chain). This "down-cycling" can mean that the secondary material cannot directly replace a primary material on a like-for-like basis. Possible consequences are:

    - Lower amount saved (more of the secondary material might be needed to perform the same function or it might have a shorter lifespan;
    - Other material saved (e.g. when mixed plastics are used to make products that should have been produced using wood or cement);
    - Need to use additives, protective layer, painting.

  These need to be considered when evaluating recycling options. Down-cycling should be considered for some materials in particular, such as wood. It is essential that the down-cycling issue and related assumptions are clearly documented in the study;

- **Identifying substituted / avoided processes.** The substitution approach is applicable in situations where the same type of material is "avoided" (e.g., recycling plastic back into plastic), or where a different type of material is avoided (e.g., recycling plastic into "plaswood", an alternative for wood used for street furniture). In each case, it is important to consider what, and how much, primary production is being avoided. There are different perspectives on how to determine this, and these perspectives consider the likely market consequences of generating secondary materials and of avoiding end-of-life treatment. The ILCD Handbook, General guide for Life Cycle Assessment – Detailed guidance[83] expands on these different alternatives in more detail. It should be consulted if a detailed LCA involving waste prevention, re-use and recycling is to be performed.

- **Checking market availability.** Substitution is only possible in case there is a sufficient demand for the recycled material. If a viable market is unavailable, the material either cannot be recycled or it will be recycled but will go to an output market that will no longer be available for another waste stream (and therefore this waste stream will no longer be recycled). Both consequences result in no net market increase for recycling and no net saving of virgin material used in production. Assessing market availability for recycled materials is a critical step in the LCA process. When the market appears limited, its impact should be evaluated through sensitivity analysis.

[83] http://lct.jrc.ec.europa.eu/assessment/projects

9.5.3 Modelling recommendations

The main recommendations are:

- Analyse the material losses across the collection/sorting/recycling chain; in particular, recycling rates may refer to pure material or gross weight (including impurities); in the first case, losses of the subsequent processes must be expressed in % of the incoming pure material;
- Analyse the substitution thoroughly: which material is saved? How much? Are additional processes necessary (additives, painting, protection…)? In case of doubt about the most adequate modelling, a thorough sensitivity analysis should be performed;
- Consider the recommendations of the ILCD Handbook;
- Check the final destination of the recycled material and the impacts corresponding to transport storage and use.

9.6 Composting

9.6.1 Overview

There is a large variety of composting technologies. Composting can be performed in private gardens (home composting), on field (agriculture residues left in/on the soil) as well as in advanced centralised plants. Industrial plants can be open or closed:

- Open composting may have drawbacks, such as risk of odour emissions (though this can be markedly reduced if the composting process is well managed) and high area demand. The duration of the composting process, depending on the mixing frequency, may vary from 3 to 6 months;
- Closed plants allow for a significant odour minimisation. The gas emissions in such plants are collected and fed through a purification system (usually a biofilter). Another advantage of such plants is the automatic moisture and oxygen control, which allows acceleration of the composting process.

The control of compost processing is based on the homogenisation and mixing of the waste while providing the necessary aeration and humidification. After the quality of the input waste material, good operation is the second key requirement to produce high quality compost and avoid toxic/odorous atmospheric emissions.

Both bio-waste from households and from garden waste are suitable for composting. However, as opposed to digestion, a good structure of the biodegradable waste is needed in order to ensure good penetration and distribution of oxygen in the material. Other pre-conditions for composting include: appropriate nutrients ratio and sufficient material moisture. The optimum carbon/nitrogen for composting lies between 20 and 40. The water content for optimal process performance is limited by the required void volume pores for aeration.

There are significant technical differences among composting plants, as well as significant differences in the performance of the individual plants. Therefore, it is important to use plant-specific information for the waste type defined by the system description and within the geographical and spatial boundaries defined in the scope of the study. If specific data are not known (e.g., plant is not built), a sensitivity analysis should show how sensible results are as a function of the quality of technologies and operation.

LCAs considering composting can, by lack of data, neglect benefits such as soil health and fertility, reduced pesticide consumption, substitution of mineral fertilisers, improved workability and water retention capacity, reduced irrigation needs, etc. However, those are essential benefits of compost and should be mentioned, at least qualitatively in both inventory and assessment stages[84].

Figure 15 gives an example of a typical structure for a composting plant.

[84] For more information see the document " *Supporting Environmentally Sound Decisions for Bio-waste Management - A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) in the context of bio-waste management* " developed by the Joint Research Centre (JRC) in cooperation with the Directorate General Environment (DG ENV)

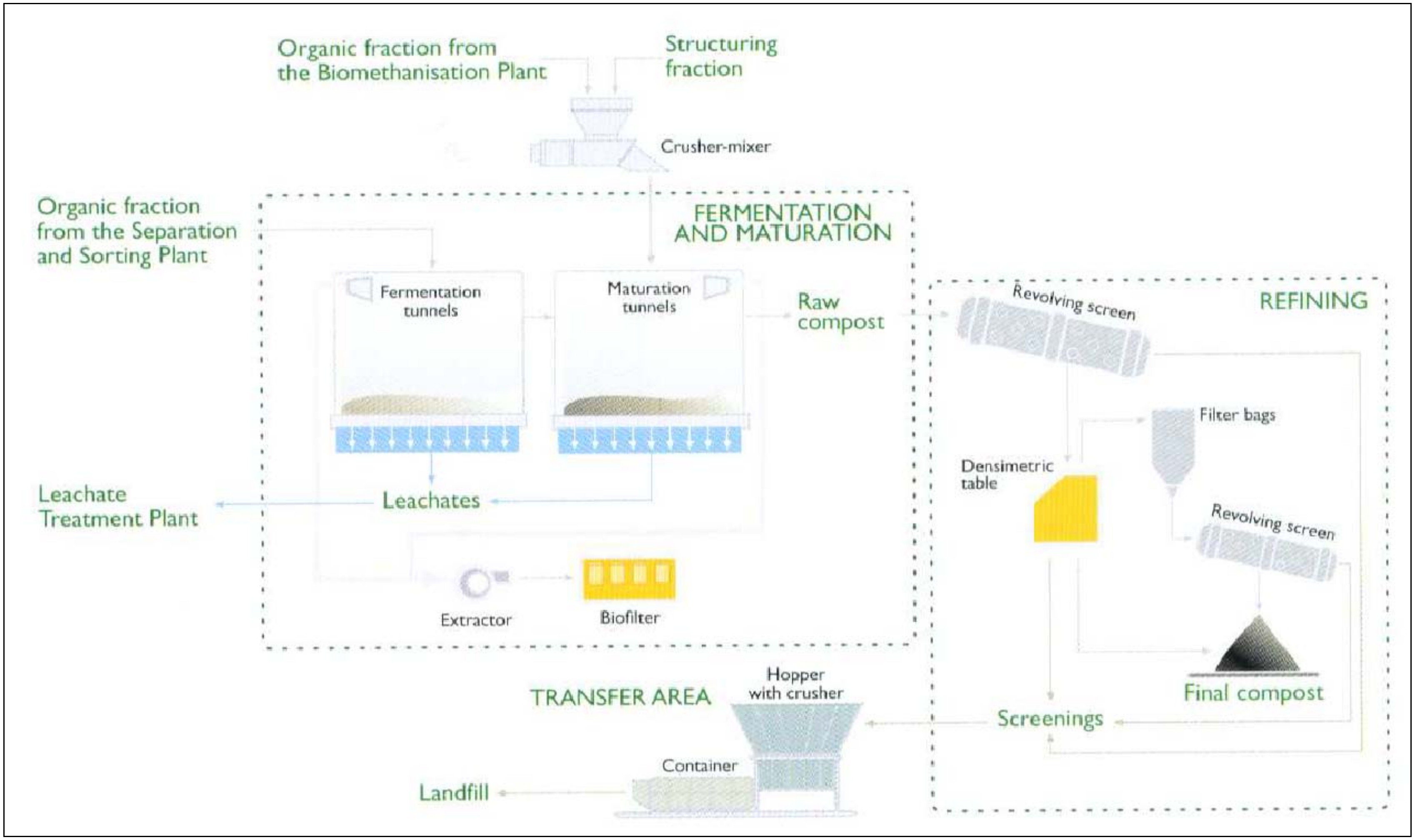


Figure 15: Composting plant display diagram[85]

[85] From a brochure prepared by the City of Madrid (Area de Gobierno de Medio Ambiente) about the Valdemingomez Technological park and particularly the Las Dehesas Waste Treatment Center

9.6.2 Key technical and modelling aspects

9.6.2.1 Emission of CO_2 and CH_4

As long as organic waste is treated with sufficient oxygen excess, emission of CH_4 is negligible compared to the CO_2 emissions. Waste oxygenation is achieved by mixing the waste regularly to allow oxygen to penetrate the organic matter at depth where the composting chemical reactions take place. If degradation of the organic fraction is not fully achieved when the composting process is stopped, the degradation will continue spontaneously but slowly. Ultimately, possibly with some delay, the same quantity of carbon will be emitted by all composting methods. The main difference will arise from methane emission, when relevant.

Carbon storage and delayed emissions:

Carbon storage should be reported separately. By default they should not be included in the analysis or when deriving recommendations.

"*They require special or separate analysis only if such is included in line with an explicit goal requirement: Separately analyse and jointly discuss the results including and excluding carbon storage and delayed emissions / re-use/recycling/re-use credits*." **[86]**

See also ILCD Handbook General Guide for LCA – Detailed guidance:

- Chapter 7.4.3.7.3 "Temporary carbon storage, delayed greenhouse gas emissions, delayed credits for solving multi-functionality";
- Chapter 14.5.3.5 "Time aspects in “delayed” recycling of long-living products".

Calculation based on composition

The quantity of CO_2 released into the air can be estimated using the empirical approach, i.e., by multiplying the mass of incoming carbon by the % (mass) that degrades (e.g., for garden waste containing for instance 184 g C/kg of waste, a ~65% degradation can be assumed). The estimated carbon content must consider the type of waste and the humidity. When relevant (no biofilter, not enough mixing), CH_4 emissions should be approximated, based on similar cases and situations.

Typical process data

If the composition is not (well) known but data are available from plants treating similar waste, emissions can be derived from emissions records (specific or from literature). If some information is available about the carbon content of the waste it should be used to correct the carbon balance. In all studies, LCA practitioners should control that the carbon input and carbon output are equal in all compared waste management options.

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[86] ILCD Handbook General guide for LCA – Detailed guidance: Provisions 9.4

9.6.2.2 Other emissions to air

In addition to CO_2 and CH_4, the main emissions to air are N_2O, NH_3 and odorous components. Emissions to air should be estimated based on the waste composition (mainly nitrogen content) and distribution factors to air, water, compost and residue. Distribution factors from literature should be sensitive to the waste composition.

If specific data (i.e., data from the target plant, treating the target waste) are available, they are preferable to data from modelling simulations. In case modelling cannot be applied and there are no specific data, secondary data should be used with caution. In particular, the technological representativeness should be controlled because there might be great variations among plants (types). Because closed composting methods collect and efficiently filter their air emissions, their toxic gaseous emissions (other than CO_2) should be negligible.

For open processes, emissions to air depend on how the composting process is conceived and operated. Efficiency data can be collected from scientific studies and from control equipment suppliers. Biological filters are the most common emission purification technology.

9.6.2.3 Emissions to water

The composting process produces variable amounts of leachate (water originates either from the waste itself, from compost humidification and/or from rainwater). As the composting process is exothermic, compost is warm (about 70°C). This leads to water evaporation in a closed composting process. This water condenses in colder areas of the plant (walls), is recovered, may be treated and either put back on the compost or released. If the condensate water is returned to the composting process, water emissions are usually negligible. Otherwise, the captured condensate, in case of central composting, is collected and purified in a local wastewater treatment unit, or sent to the municipal water collection and treatment system.

In other cases (no leachate collection), the emissions depend on the concentration of pollutants in waste and in the evaporated water. Data can be derived from the specific plant or from literature. In the second case, LCA practitioners should discuss the uncertainty about those emissions and its effect on the uncertainty about the results.

In case of home composting, it may be assumed that pollutants emitted in run-off water are insignificant as long as the waste is garden waste. However, this assumption should be assessed in a sensitivity analysis.

9.6.2.4 Emissions from home composting

Few data are available in the literature about the environmental impacts of home composting. The main findings are:

- Lack of comprehensive studies on emissions of home composting;
- Lack of studies regarding the environmental impacts of various home composting practices depending.

To assess the environmental impacts, results from experimental approach in laboratory can also be used. Emission estimates are appropriate for the following:

- People who properly manage their home composting process: regular waste mixing (and thus aeration), balanced input material, proper location (to favour high temperature) and humidification;
- People who do not do it properly. This may result in undesirable emissions (e.g., CH_4, H_2S) due to anaerobic conditions and produces less stable and less hygienic compost.

Many surveys have shown that a significant fraction of home composters do not manage the process properly.

Recent experimental data were produced by Andersen et al. (2010)[87]. The emissions of methane (CH_4) and nitrous oxide (N_2O) were quantified as 0.4–4.2 kg CH_4 /t input wet waste (ww) and 0.30–0.55 kg N_2O /t ww, depending on the mixing frequency. This corresponds to emission factors (EFs) (including only CH_4 and N_2O emissions) of 100–239 kg CO_2-eq. /t ww. The GHG emissions (in kg CO_2-eq. /t ww) from home composting of organic household waste were found to be within the same order of magnitude as for centralised composting plants.

9.6.2.5 Physico-chemical and biological effects of compost recovery

Spreading

The main environmental impact associated with this process is the consumption of equipment fuel and related combustion exhaust gases.

The spreading process itself does not differ much between commercial fertiliser and compost. However, the amount of compost that is required per unit area is greater, which increases the energy use for compost transport and spreading. If fertiliser and compost spreading can be regarded as equivalent processes, this process will not have

[87] J.K. Andersen, A. Boldrin, T.H. Christensen and C. Scheutz: Greenhouse gas emissions from home composting of organic household waste. *Waste Management*, 30 (2010) 2475–2482

to be taken into account in the modelling process. If not considered in the composting analysis, spreading should be also left out when modelling the saved fertilizers.

Market outlet is a very important issue which must be clearly documented and discussed.

Nutrients supply

Compost contains nutrients that reduce the need for fertilizers or organic amendment (e.g., peat) when spread on land. This saving must be considered as follows:

- The amount of available nutrients contained in the compost: mainly nitrogen (N) and phosphorous (P), Potassium (K) and Calcium (Ca). LCA practitioners should not consider the literature-based average nutrient content of compost, but should use the nutrients content of the compost being studied. The compost composition can be derived from the composition of the composted organic fraction (e.g., compost produced from a fraction poor in N will contain less N (not proportionally because some N is emitted to air and water) and will allow for a smaller saving of nitrate fertilizer;
- Farmers who properly manage their soil quality with fertilizer/compost can achieve a replacement ratio close to 1:1 or above (as bio-availability of NPK in compost is higher than for artificial fertilizers). However, it is common practice that farmers over fertilize to ensure that their crops have adequate nutrient supply. This behaviour might depend on the type of crops. Recommended agronomic doses for N and P in soil should be used for guidance (kg/ha-year). The ratio between recommended N-dose and recommended P-dose can be used as a reference value. If the exploitable N/P ratio in compost is larger than the reference value, the compost is N-limited and vice versa.
- Nutrients in compost are generally more stable (less mobile to produce leachate) compared to commercial fertilizers. Hence, when using compost as a fertilizer substitute, it is not necessary to over fertilize to compensate for nutrient leaching. When applied properly at the correct agronomic rates, compost reduces the concentrations of nutrients that can leach to groundwater and surface water.
- Compost generally substitutes for peat on a volume rather than mass basis (cf. Smith et al 2001[88]; Boldrin et al 2010[89]). Several values exist in the literature for the volume reduction of green and food waste through the composting process.

[88] Smith, A., Brown, K., Ogilvie, S., Rushton, K. & Bates, J. (2001) Waste Management Options and Climate Change. Final report to the European Commission, DG Environment. Office for Official Publications of the European Communities, Luxembourg

[89] Boldrin, A., Hartling, K.R., Smidt, M.M. & Christensen, T.H. (2010). Environmental inventory modelling of the use of compost and peat in growth media preparation. *Resource, Conservation and Recycling*, 54, 1250-1260

Assuming an average bulk density of 509 g/l for green waste compost and 180 g/l for peat (WRAP 2003[90]), this equates to 0.35 kg of peat displaced for every kg of green waste compost. For digestate, a density of 468 g/l is recommended (Fuchs 2008[91]), meaning 0.38 kg of peat is displaced for every kg of digestate.

Use of compost as a substitute for the carbon contained in peat has important climate implications. Large amounts of carbon are stored in the world's peat bogs. However, when the peat is extracted it becomes exposed to aerobic conditions. Peat used as a growing medium or soil conditioner mineralises rapidly, releasing carbon as CO_2. A small fraction of the carbon from peat will be sequestered in stable humic compounds. Substituting compost for peat:

1. Reduces CO_2 emissions associated with peat mineralisation;
2. Reduces emissions associated with transporting and harvesting peat;
3. Avoids drainage of peat bogs and the associated adverse ecological impacts arising from the destruction of an increasingly rare resource/habitat). However, consideration of this effect (i.e., assessing land use changes) in an LCA is currently only under development.

Other benefits

Using compost has numerous other technical advantages that should be regarded separately from the LCA, although most effects are indirect and their relevance should be carefully evaluated in comparison to the better understood and quantifiable benefits of fertiliser replacement[92]:

- It improves soil structure and texture (this helps reduce erosion, reduce leaching, improves germination, increases water storage capacity and thus reduces irrigation needs and storm-water run-off.);
- It increases soil cation exchange capacity;
- It increases soil microbial activity (e.g., increased pathogen resistance, lowering the need for pesticides and fungicides);
- It enhances carbon storage in soil (note that this is excluded from LCA analysis and decision support);

[90] WRAP (2003). Compost and Growing Media Manufacturing in the UK, Opportunities for the Use of Composted Materials. WRAP Research Report, Banbury

[91] Fuchs, J.G., (2008) Pres.Nr. 19 Effects of digestate on the environment and on plant production - results of a research project ECN/ORBIT e.V. Workshop 2008„The future for Anaerobic Digestion of Organic Waste in Europe"

[92] "Life cycle inventory and Life cycle assessment for windrow composting systems." Report prepared for NSW Department of Environment and Conservation (sustainability Programs Division) Published by Recycled Organics Unit, The University of New South Wales Sydney Australia, 2006.

- It increases the soil organic carbon content and hence improves long term soil productivity. Hence, a smaller land surface is necessary for the same crop production, reducing the associated agriculture impacts commensurately;
- It may reduce the need of pesticides (higher microbiological diversity);
- It can reduce soil acidity (when containing lime).

Drawbacks

Depending on the organic source, compost frequently contains some pollutants that can be transferred to the soil. The pollutant concentrations in compost depend on the contamination levels in the origin flows (wastewater and organic waste) and the technology applied to treat these flows.

These additional effects are difficult to quantify and consider in an LCA. However, these issues should be presented and discussed in the results of the study.

9.6.3 Modelling recommendations

9.6.3.1 Modelling the use of compost

Modelling the benefits of using compost as a substitute for fertilizers should not be limited only to saving fertilisers. There are many other indirect environmental effects which still need research in order to develop LCA tools and account for these benefits properly. If compost cannot be recovered, the potential impacts of its disposal should be estimated.

9.6.3.2 Modelling transport and spreading

Compost transport and spreading generally has lower relevance than other composting steps; however, because of the lower nutrient density of compost compared to mineral fertilizers, compost transport and spreading require more energy and human effort per nutrient amount delivered. Therefore, transport and spreading should not be neglected.

9.6.3.3 Emissions

Emissions include:

- An elemental mass balance should be performed for the main components (C, N, P, K) to ensure that the same input and output are used for all compared systems. If data originate from different, incoherent data sources and elemental balances do not match, corrected emissions figures should be calculated and used;

- Emissions from the composting process (possibly after biofilter) and from degradation of compost on the field should be included in the inventory, especially CO_2 (ensure correct balancing with uptake in the biomass), CH_4, N_20, NH_3, CO, and – if leachate occurs – NO_3^-, PO_4^{3-}, NH_3/NH_4^+, metals, TOC.

9.7 Anaerobic digestion

9.7.1 Overview

Anaerobic digestion (AD) is a treatment process for biodegradable substances that is performed under anaerobic conditions in which those biodegradable substances are decomposed by micro-organisms in order to generate biogas; the biogas is used as a source of energy, generally, to produce electricity.

The AD inputs include a variety of substrates such as:

- Food waste;
- Paper and cardboard;
- Edible oil and fat;
- Sludge.

The outputs of the reaction are:

- A nutrient-rich liquid digestate fraction that varies in composition according to the AD technology employed. The digestate can be spread directly on land or composted for final stabilization, provided that the quality of input material is sufficiently high. This requires a conventional composting facility similar to the one that would be needed to directly compost the same waste;
- Biogas, which is a mixture of methane and carbon dioxide, water vapour and trace gases (e.g., H_2S).

When the solid fraction is composted, the outputs of an AD plant are similar to the outputs of the composting process for selectively collected bio-waste, with the addition of the biogas produced.

The amount and composition of the compost from AD digestate are similar as well, as are the benefits and drawbacks of using it. So, most comments and requirements concerning composting also apply to AD. However, this does not mean that the compost of digestate and the compost of the original waste are compositionally exactly the same. Benefits and drawbacks need to be checked separately from what is done for compost of waste.

In practice, market/outlet problems are much more frequent with compost of digestate than with compost of waste, primarily because of compost quality. However, this quality difference may be more related different input compositions and not to the composting process. If the quality differences appear to arise only from different feedstock compositions and not from the composting processes, the same inputs should be used in the model and the similar outputs should be modelled. However, literature is not conclusive on this point.

From an environmental viewpoint, AD coupled with a digestate composting facility is thus theoretically better than conventional composting. The impacts of each are more or less the same, but the supply of AD biogas for energy produces a net emission savings due to the avoided use of fossil fuel-derived power.

However, the produced energy can be partly offset by the AD plant own energy consumption as well as by the energy required to prepare the waste for the AD process.

AD is less common than composting for economic (lower investment, lower operation cost) and technical reasons (less restrictions concerning composition, easier to run, more flexibility concerning amount and composition of input material, higher reliability, much shorter time to start and to re-start, much less unscheduled shut-down risk)[93].

9.7.2 Key technical and modelling aspects

9.7.2.1 Biogas generation

The amount (m^3/incoming tonne) and composition (%CH_4 / %CO_2) of biogas generated depend on:

- Substrate composition: each component (protein, cellulose, hemicellulose and lignin, rapidly degradable carbohydrates, etc.) has a specific microbial degradability rate, e.g., cellulose and hemi-cellulose are generally considered to be very degradable, while lignin decomposition is limited to a low percentage range (EcoInvent 2009[94]);
- Process characteristics: hydraulic retention time, temperature, pH, quality of agitation mixing, residence time;
- Quality of operation (stabilisation of the process);

[93] For more information on the environmental performance of anaerobic digestion and composting, reference is made to the document " *Supporting Environmentally Sound Decisions for Bio-waste Management - A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) in the context of bio-waste management* " developed by the Joint Research Centre (JRC) together with the Directorate General Environment (DG ENV)

[94] Life Cycle Inventories of Waste Treatment services Part II Landfills – Underground deposits – Landfarming Swiss Centre for Life Cycle Inventories (2009)

- Feeding rate.

<u>Biogas production</u>

Some relevant parameters on biogas production are provided by the following table.

Table 8: Biogas production yield from different waste types[95]

Waste type	Biogas production		
	$m^3/t_{incoming}$	$m^3/t\ DM_{incoming}$	$m^3/t\ VM_{incoming}$
Household waste	100 to 150	150 to 400	500
Bio-waste	80 to 200	180 to 350	200 to 400
Sludge	4 to 35	180 to 490	180 to 770
Manure	5 to 140	150 to 480	250 to 600

Legend: $t_{incoming}$ = ton of incoming waste (wet) ; $tDM_{incoming}$ ton of incoming dry matter; $tVM_{incoming}$ ton of incoming volatile matter.

<u>Biogas composition</u>

The following table gives volumetric ranges for key components in biogas.

Table 9: Key components of biogas and their concentrations (% vol)[96]

CH_4	CO_2	H_2O	H_2S	N_2
50-70%	30-50%	5%	0.02-0.5%	0-5%

9.7.2.2 Saved energy production process

Energy production by combustion of biogas varies greatly depending on combustion and energy recovery technology. Biogas can be used to produce heat or electricity, as fuel for motor vehicles, or it can be injected into a natural gas grid. Biogas requires a custom engine designed to use natural gas. When injected into a natural gas grid, the biogas needs to be upgraded as such. The biogas LHV can be increased by removing CO_2, water and N_2/O_2, which has the effect of increasing methane content (approx. 60% initially) up to 95% and the gas being compressed. Further, H_2S should also be removed to avoid air pollution during combustion and to avoid corrosion of (bio)gas burning equipment. If applied, these operations should be modelled.

[95] Impacts environnementaux de la gestion biologique des déchets, bilan des connaissances, study done for ADEME (French Environment Agency) by Cemagref – INRA – Creed – Anjou Recherche – Ecobilan – Orval)
[96] « Impacts environnementaux de la gestion biologique des déchets, bilan des connaissances » study done for ADEME (French Environment Agency) by Cemagref – INRA – Creed – Anjou Recherche – Ecobilan – Orval)

The following steps should be applied when identifying substituted energy sources:

- Quantify the distribution of the total exploited energy among district heating, electricity production and fuel for car or bus;
- Check with the companies that use biogas to document the alternative energy source(s) that they would use if the biogas was not provided;
- Check with the electricity producers to document the alternative energy sources that would be use for electricity production if the biogas was not used..

For more details see Annex C6.

9.7.2.3 Emissions to air

The processes contributing the most to the (saved) emissions are biogas substitution for fossil fuel combustion and the avoided environmental burdens arising from the (avoided) energy production process. Flue gas composition is similar to the one of natural gas burning, with some dilution due to the presence of CO_2. It may be approached as considering flue gas = CO_2 in biogas + flue gas that would be obtained by burning only pure gas or biogas. Note that CO_2 emitted from biogas burning is biogenic and should therefore be reported separately as “Carbon dioxide (biogenic)” as “Emissions to air”.

In addition, some smaller flows that are worth considering include:

- Emissions from storage before treatment (as the degradation process starts spontaneously);
- Direct emissions from the degradation process (leaks);
- CH_4-slip at the burning of $CH_{4;}$
- Fugitive biogas escaped during storage (at combustion site). Some published emissions values are given for each of these categories and these may be used in a first iteration of the calculation:
    - ⇒ IPCC: between 0 and 10% of the amount of biogas generated. They recommend a default value of 5% in the absence of specific data. For modern plants, fugitive emissions are negligible[97];
    - ⇒ ERM study[98]: 0.5%;

[97] IPCC (2006), Guidelines for National Greenhouse Gas Inventories: Chapter 4: Biological treatment of solid waste.
[98] Fisher, K., Aumonier, S. (2006), Impact of Energy from Waste and Recycling Policy on UK Greenhouse Gas Emissions, ERM for DEFRA

⇒ The AEA study[99] shows that small fugitive biogas emission may have a significant impact on the overall balance of GHG emissions from a biogas plant.

9.7.2.4 Emissions to water

Water emissions in the digestion plant mainly occur during the fermentation phase. Some heavy metals and nutrients leach into the water effluent; the remainder is retained in the digestion residue and, thus, becomes part of the compost (in the compost maturation phase, additional leaching will involve nitrogen, but neither metals nor other nutrients). The amount of rejected water and pollutants content vary greatly depending on applied technology. Therefore, it is recommended to only use data specific for the relevant technology (or the plant itself), avoiding the use of generic data.

Specific models are useful to estimate emissions to water; frequently, an empirical approach is applied which is based on the waste flow composition and distribution factors (among emissions to air, emissions to water digestate and other residues).

Different process-specific emission factors are available in the literature. They concern raw emissions, possibly upstream any water treatment. These emissions will be significantly reduced if water treatment is applied. When using data, LCA practitioners shall check if the wastewater treatment is taken into account or not.

9.7.2.5 Valorisation of digestate

The digestate may sometimes require drying prior to being separated into the following fractions:

- **Fibers**, which in some cases can be directly used as soil amendment with low fertilizer content. Preferably, it can be composted to generate relatively good quality compost;
- **Effluents**, which contain large quantities of nutrients. The effluent can be spread on fields for its high fertilizer content to allow a full transfer of nutrients to the underlying soil. However, the liquid form of this nutrient-rich mixture poses increased risk for groundwater and surface water pollution. In practice this type of valorisation is limited.

[99] Figures come from the study “Waste management options and climate change” study done for the European Commission, DG-Environment by AEA Technology (2001)

A common alternative is to recycle these effluents in the AD process in order to retain the nutrients in the solid compost fraction that is delivered to the field. The associate advantages (e.g., less water pollution and better use of nutrients) should be reflected in the LCA modelling. However, if its ammonia content is high, the compost might become too rich in nitrogen and might result in water pollution by nitrates.

9.7.2.6 Allocation

When the AD technology is assessed in the framework of a waste specific stream of organic waste, impacts and saved impacts of the mix stream can be allocated to the different streams, preferably proportionally to a relevant parameter (e.g., carbon content, individual Lower Heating Value).

9.7.3 Modelling recommendations

9.7.3.1 Mass balance

An elemental mass balance should be performed for the main components (C, N, P, K) to ensure the same input and output are used for all compared systems. If data originate from different, incoherent data sources and balances do not match, corrected emissions values should be calculated and used (cf. 8.2.1).

9.7.3.2 Use of biogas

The benefits of using biogas largely depend on the way it valorised and the saved energy from other energy sources. If no specific use is decided yet, a sensitivity analysis should be performed.

Modelling energy recovery may require sophisticated modelling. The greater its importance in the LCA, the more sophisticated the associated modelling should be. Particular attention should be paid to:

- Definition of efficiency by data providers;
- Permanence of the energy requirements by energy users (e.g., if the energy is only used part-time, it will be wasted for the remaining time, unless an alternative consumer is available).

9.7.3.3 Modelling of composting of digestate

LCA practitioners should include both biogas valorisation and compost valorisation in the analysis of an AD process. Modelling AD and composting of digestate requires either a thorough analysis of the effective valorisation of outputs (preferably for existing plants) or a sensitivity analysis to show the effects of limited output markets (for new plants).

9.8 Mechanical-Biological Treatment

9.8.1 Overview

Mechanical-Biological Treatment (MBT) consists of a mechanical pre-treatment to separate the non-degradable fractions followed by a biological treatment of the remaining waste prior to landfilling. The biodegradable fraction is composted (or anaerobically digested) and valorised, or landfilled (most frequent case). One common reason to use MBT is the need to comply with the Landfill Directive (1999/31/EC) targets on reduction of landfilling of biodegradable waste.

The biological process in the aerobic MBT is conducted as a classic composting process (on selected organic fractions). In the anaerobic MBT, the biological process consists of an anaerobic digestion stage producing biogas. MBT plants combine several types of waste treatment (sorting, biological treatment, etc.). The considerations presented above for these processes remain valid. A wide range of plant configurations exist that also affect the quality of the output material.

The following outputs can be recovered from MBT facilities:

- Compost, not suited for application on soil because of the high contamination risk; this is more likely to be called Compost-Like Output (CLO). The organic fraction is bio-stabilised. This has the advantage of reducing biodegradation inside the landfill and the associated odours and methane emissions;
- Recyclable materials (e.g., metals, plastics), containing more impurities than materials from selective collection (of packaging);
- Biogas (in case anaerobic digestion is applied). However, application of AD to “dirty” bio-waste, i.e., to that derived from mechanical sorting of mixed waste, has often proved to be very critical for the process itself (clogging of the reactor due to inert materials, etc.);
- Refuse Derived Fuel (RDF), i.e., pellets of fluff with high caloric value, for energetic valorisation.

9.8.2 Key technical and modelling aspects

The same modelling principle as for sorting plant, AD or composting plant shall be followed.

9.8.2.1 Extraction efficiency

Extraction efficiency depends greatly on the design and operation (speed, control, fine tuning, etc.) of the plant. Hand separation for large pieces, multiple separation steps (combining different kinds of separation techniques), visual control, proper maintenance (e.g., avoiding obstruction of holes in a trammel), and final visual control by humans are key factors necessary to increase the proportion of targeted materials that can be effectively extracted and their quality (purity). Consequently, data from literature should be used with caution.

9.8.2.2 Direct impacts of the sorting plant

The environmental impacts of the sorting plant are generally small (<10% of recycling benefits for energy consumption), mainly arising from electricity consumption and some fuel (bulldozer engines). Noise can also be a significant impact. Data from the literature can be used and extrapolated proportionally to the plant capacity and the number of separation steps.

9.8.2.3 Market outlets

The major concern is finding market outlets. Concern about the marketability of the outputs from MBT processes is the single most significant factor constraining the environmental balance of MBT processes. The recovered outputs that cannot find a use are likely to be landfilled.

The following outputs could be recovered from MBT facilities:

- Compost-like output (CLO)

  In the case of compost-like applications, the main issue is the quality of the material, especially the higher level of contamination of MBT compost compared to compost produced from separated collected green waste. This limits the end-uses for this material (e.g., visual contamination, presence of heavy metals, etc.) as compost. Compost from MBT output frequently does not meet the specifications for compost and, therefore, cannot be applied in agriculture. Most potential benefits of compost are therefore lost.

- Refused Derived Fuel (RDF) (Note: RDF is also referred to as SRF (Solid Recovered Fuel)

RDF consists of waste wood and paper, waste plastics, carpets, etc. There are European Standards for quality of Solid Recovered Fuels (SRF) prepared by the European Committee for Standardization (CEN)[100]. In particular, reference shall be made to the CEN/TC 343[101]. Certified SRF is an alternative to solid fuels in the cement industry, in cogeneration plants of the pulp and paper industry, in integrated chemical.

RDF can replace gas, especially in co-firing with biomass in cogeneration power plants; this may allow for better burning behavior leading to increased efficiency and lower maintenance.

Today – and particularly in advanced energy recovery countries – calorific MBT fractions are one outlet for manufacturers of RDF, oriented to the requirements of different down-stream users. However, calorific MBT fractions are frequently unprocessed for further use as fuel and, therefore, are unattractive for a mix of technical, economic, legal, and regulatory reasons. LCA practitioners should confirm the real use of RDF and model it accordingly. In case of doubt, a sensitivity analysis should be performed.

- Recovered recyclables: plastics, metals, etc.

If markets for recyclables are not sustained, this could lead to low quality application (e.g., recycled PE from MBT could be used to produce (low-quality) pipe for application in the construction sector, mainly in non-visible applications where aesthetic aspects are not considered) or output being classified as residues and the end-use being counted as disposal.

The impacts on the downstream cleaning/treatment steps shall be studied and evaluated if necessary (e.g., additional consumption of water and detergent for plastics recycling process, second grinding process to recover metal).

9.8.3 Modelling recommendations

9.8.3.1 Use specific extraction efficiency figures

Because design and operation vary significantly among MBT plants, the extraction efficiency of the plants also varies accordingly (e.g., from 40% to 90% for plastic bottles). For existing plants, specific data should be used. For new plants or existing

[100] http://www.cen.eu/cen/Pages/default.aspx
[101] http://www.cen.eu/CEN/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/Standards.aspx?param=407430&title=CEN/TC+343

plants that should be upgraded, the plant design (and operation) should be considered to estimate the extraction efficiency for each targeted material. In all cases, a sensitivity analysis is required.

9.8.3.2 Analyse market outlets

Modelling MBT requires either a thorough analysis of the effective valorisation of outputs (preferable for existing plants) or a sensitivity analysis to show the effects of potential limited output markets (new plants).

Future technologies and dedicated recycling plants (with improved cleaning, separation and purification techniques) should be considered for strategic (long-term) decision-making.

9.9 Waste Incineration

9.9.1 Overview

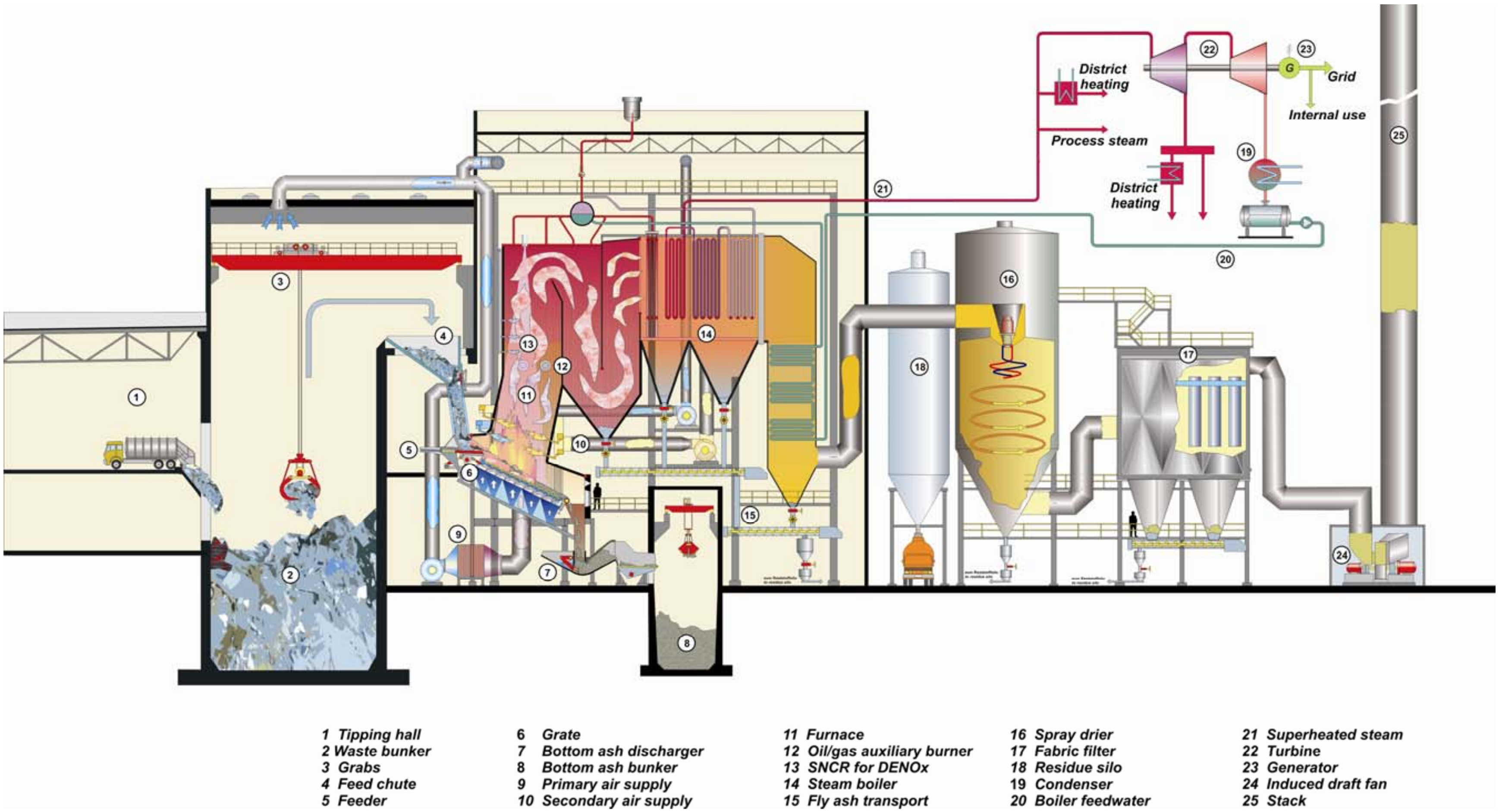

Figure 16: Waste-to-Energy process diagram[102]

[102] Kindly provided by the Confederation of Waste-to-Energy Plants (CEWEP)

In Europe, the reference directive for waste incineration is the so-called Waste Incineration Directive (WID) (Directive 2000/76/EC)[103]. This directive aims at reducing the negative environmental effects from the incineration and co-incineration of waste. This applies in particular to emissions to air, soil, surface water and groundwater, as well as to risks to human health.

As defined in the Reference Document on the Best Available Techniques (BREF) for Waste Incineration (2006)[104], waste incineration is the oxidation of the combustible materials contained in the waste. During incineration, flue-gases are created that will contain the majority of the available fuel energy as heat. The actual combustion process occurs in the gas phase and lasts for a fraction of a second, simultaneously releasing energy. Where the calorific value of the waste is sufficient (which is normally the case in Europe for municipal solid waste and commercial waste), this leads to a thermal chain reaction and self-supporting combustion, i.e. there is no need for the addition of other fuels under normal operating conditions. Addition of fuel is, however, necessary during start-up and shut-down phases (legal request).

In the course of the operation of waste incineration plants, also referred to as Waste to Energy (W-t-E) plants, emissions and consumption issues arise, the magnitude of which is influenced by:

- Waste composition (calorific value, humidity, pollutants content, carbon content, inert content, etc.);
- Plant design: furnace type (grate incinerator, rotary kiln, fluidized bed, etc.), type of flue gas treatment (dry, semi-dry or semi-wet, wet), NO_x removal (selective catalytic reduction – SCR, selective non catalytic reduction – SNCR), wastewater treatment (in case of wet scrubbing);
- Operation: quality (frequency) of maintenance, end-of-life routes for residues, good waste mixing for stable operation. However, the legislation on waste incineration plants is the most stringent of the industry and the actual emissions to air and, if any, to water are very low.

When the environmental impacts of the W-t-E plant play a crucial role in the results and the conclusions, average values from a database may not be sufficient and specific models should be applied to obtain a more representative model of the emissions and energy recovery.

9.9.2 Key technical and modelling aspects

9.9.2.1 System limits

The incineration process requires a number of inputs (reagents, electricity, water, fuel, etc.) and provides energy (electricity, steam, hot water). In addition, incineration produces different

103 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:332:0091:0111:EN:PDF

104 Integrated Pollution Prevention and Control - Reference Document on the Best Available -Techniques for Waste Incineration - August 2006 - European Commission

residues, which require treatment. Therefore, consumption of inputs and treatment of residues should be included within the system boundaries.

9.9.2.2 Selection of type of furnace

The different types of furnaces have specific characteristics that make them more suitable for certain types of waste. BREF (2006)[105] gives details on the most common combinations of furnaces and waste flows. LCA practitioners should check that the type of furnace they are modelling is suitable for the type of waste they are studying.

9.9.2.3 Variable composition

The impacts of incineration are very sensitive to the composition of the waste being incinerated. Since waste composition may vary significantly, the impacts from incineration is highly variable. Therefore, modelling should be preferred to using life cycle inventory (LCI) data from databases (unless composition is close to the reference composition of the database or the impacts of incineration have insignificant influence on the results (e.g., in the case of burning residues from a sorting process). For example, when W-t-E is compared for instance to anaerobic digestion (AD) or composting, only the impacts of burning additional amount of bio-waste need to be attributed to W-t-E.

Specific cautionary remarks are given below for some waste streams.

- Sewage sludge (BREF incineration, 2006):

Dry solids content is a key factor to consider when incinerating sewage sludge (typically it varies from 10% up to 45%).Sewage sludge frequently has a high water content and t requires drying before combustion, or the addition of supplementary fuels to ensure stable and efficient combustion. Because the environmental impacts/benefits of incinerating sewage sludge are closely linked to its dry content, accurate information related to the physical characteristics of the target sludge is necessary to conduct a valid LCA.

- Clinical waste (BREF incineration, 2006):

Higly variable calorific values and moisture contents are key factors to consider when incinerating clinical waste. For example, clinical waste often contains materials with very high Net Calorific Value (e.g., plastics), but also it also contains residues with very high water content (e.g., blood). Clinical waste, therefore, usually requires long incineration times to ensure thorough waste burnout and that the residue quality is good. In normal operation no external fuel is required to obtain the target combustion temperature.

- Hazardous waste:

Hazardous wastes tend to vary widely in composition and may contain high concentrations of corrosive substances in the raw gas (e.g. chlorines). Consequently, safeguarding the boiler from corrosion and installing adequate flue gas cleaning processes are key considerations for hazardous waste incinerators.

[105] Integrated Pollution Prevention and Control - Reference Document on the Best Available -Techniques for Waste Incineration - August 2006 - European Commission

9.9.2.4 Modelling energy recovery

Annex II of the Waste Framework Directive (Directive 2008/98/EC) provides a classification of the recovery operations into 13 classes (R1 to R13). This includes incineration facilities dedicated to the processing of municipal solid waste, for which energy recovery efficiency thresholds are introduced. The efficiency of the energy recovery operation should be estimated as follow:

Equation 4

$$\text{Energy efficiency} = (Ep - (Ef + Ei)) / (0.97 \times (Ew + Ef))$$

In which:

- *Ep (GJ/year)* stands for the annual energy produced as heat or electricity; it is calculated with energy in the form of electricity being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1;
- *Ef (GJ/year)* stands for the annual energy input to the system from fuels contributing to the production of steam;
- *Ew (GJ/year)* stands for the annual energy contained in the treated waste calculated using the net calorific value of the waste;
- *Ei (GJ/year)* stands for the annual energy imported excluding Ew and Ef;
- *0.97* is a factor accounting for the energy losses due to the bottom ash and radiation.

Efficiency of energy production

The energy production per tonne of waste for a W-t-E plant is largely proportional to the waste calorific value. Complete LCI data sets for incineration of a range of materials are provided by CEWEP via the ELCD database[106]. The attached study report of these data sets has more technical details about waste incineration from LCA perspective.

The combustion energy is used to produce steam (with an efficiency[107] of 80% or more in modern boilers associated with MSW grate processes) that can be used to produce electricity and/or heat (directly as steam or to heat water). Typical values for modern plants are:

- 20% overall efficiency to produce electricity from MSW in grate furnaces[108];

[106] http://lct.jrc.ec.europa.eu/assessment/data
[107] Efficiency is defined as the ratio between the energy of the steam output and the energy of the flue gas.
[108] Efficiency is here defined as the ratio between electricity generated by the turbine generator and heat produced by combustion.

- Because there is little heat loss at the heat exchanger, the heat is available as steam or hot water with an efficiency of roughly 80% when the plant does not generate electricity. If the efficiency is calculated based on the combustion heat, then it is smaller because part of the energy is lost in the furnace and in the bottom ash. When the W-t-E plant generates electricity and sells heat (Combined Heat and Power - CHP), up to 80% of the energy of the flue gas is available as steam or hot water. Those values are only applicable in case the heat is used permanently. In practice, those values are only achieved in a limited number of plants and real data should be used for specific studies.

The higher efficiency of heat production compared to electricity production does not imply it is better from an environmental viewpoint:

- Heat recovery saves a process (heat production) that is highly efficient (85-106% based on Net Calorific value) while
- Electricity production saves a process with a much lower efficiency (from 32% to 60% if produced from fossil fuels).

Those effects can compensate each other and ultimately the amount of primary energy saved can be similar for both options. For example, burning 10 MJ of fuel produces

- 2 MJ of electricity (20% efficiency). The (saved) electricity would have been produced with an efficiency of 40%, i.e. consuming 2 MJ /40% = 5 MJ of fuel
- Or 5 MJ of heat (50% overall efficiency). The (saved) heat would have been produced with an efficiency of 100%, i.e. consuming 5 MJ /100% = 5 MJ of fuel

Allocation of produced energy to the waste components

The net energy produced by an incineration plant is the difference between the rough energy production and the internal consumption for running the processes. Different allocations rules apply for rough production and internal consumption:

- The rough electricity production should be allocated to the different burned waste components proportionally to their net calorific values;
- The electricity consumption (including indirect for compressed air) should be allocated proportionally to the energy requirement. As this consumption is rather small (about 10-15% of production), directly allocating the net electricity production is often acceptable. If production and consumption are modelled separately, consumption can be allocated proportionally to the flue gas for fans and proportionally to the metal content for electromagnetic removal.

The following steps should be followed when identifying substituted energy sources:

- Quantify the distribution of the overall exploited energy among district heating and electricity production;
- Check with the companies that use the heat to determine what they would use as an alternative heat energy source(s) if the W-t-E heat was not available;
- Use the national grid mix per default, if the electricity would be inserted into the national grid.

For more details see Annex C6.

9.9.2.5 Emissions to air

If there are no arguments for restricting the number of analysed pollutants, the parameters regulated in the EU Incineration Directive (2000/76/EC)[109] should at least be taken into account in the scope of the LCA. The Industrial Emission Directive (IED) (2010/75/EC) should also be considered. This directive, adopted in November 2010, lays down rules on integrated prevention and control of pollution arising from industrial activities as well as rules designed to prevent or reduce emissions into air, water and land, and to prevent waste generation.

Emissions at waste incineration plants are mainly influenced by:

- Waste composition and content;
- Furnace technical measures (design and operation);
- Design and operation of flue-gas cleaning equipment.

As presented in the Riber (2007)[110] study, emissions to the environment from incineration can be split in two categories:

- Emissions directly connected to the waste (**waste specific emissions**);
- Emissions related to the process (**process specific emissions**), either because the process limits the emission or because the process produced the emission.

As carbon in waste is fully converted into CO_2 and it is not captured by the FGC, CO_2 emissions should be allocated proportionally to the combustible carbon input. The inventory should distinguish biogenic and fossil CO_2 emissions based on the waste composition and the fraction of the carbon from biogenic origin.

Incineration of waste produces air emissions of mainly dioxins, non-methane volatile organic compounds (NMVOCs), CH_4, N_2O, CO, NO_x, HCl, HF, SO_2, CO_2, H_2O, and dust. Those emissions are partly waste specific. For instance, emissions of HCl and SO_2 would not occur if Cl and S were not present in the input waste. However, the emission of these substances to air is controlled by the Flue Gas Cleaning (FGC) system. The result is that there is no proportionality between the waste concentration of a certain element (e.g., Cl) and the corresponding concentration (e.g., HCl) in the flue gases.

Those process emissions should be allocated proportionally to the calorific value (or the oxygen demand for combustion) of the waste. The rationale for this is that the amount of pollutant emitted is equal to the flue gas flow multiplied by the concentration in the flue gas. As the concentration is kept constant by the process, emissions are proportional to the flue gas flow. And as the flue gas flow is proportional to the oxygen demand (As the flue gas flow is controlled in order to strive to a targeted oxygen concentration, it is proportional to the amount of oxygen needed for the complete combustion of the waste), process emissions should be allocated proportionally to the oxygen demand for combustion.

Pollutant mass balance

[109] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:332:0091:0111:EN:PDF

[110] Christian Riber "Evaluation of Waste Specific Environmental Impacts from Incineration," Ph.D. Thesis, Institute of Environments and Resources Technical University of Denmark, October 2007

As real emission values might be readily available, it is common practice to consider emission concentrations are equal to the emission limit (or half of this limit), in order to be conservative (i.e. avoiding risk of underestimation). However, this approach is not relevant when comparing treatment options because the comparison is not fair. For comparative purposes the waste stream composition (and pollutant balance) should be the same for the compared waste treatment options in competition. For instance, if W-t-E is compared to AD and composting either

- the incinerated waste stream burned is primarily the biodegradable fraction (with very small amounts of chlorine, sulphur, fluorine, metals etc. and, therefore, generating lower emissions of HCl, HF, SO_x, dioxins, metals, and not using corresponding flue gas cleaning reagents, water, electricity, etc.), or
- the full household waste stream should be considered in both options and, as a complement to AD, a more contaminated fraction should be incinerated.

9.9.2.6 Emissions to water

Similarly to air emissions,, the EU directive on W-t-E plant lists the pollutants to include in the study when wastewater from exhaust gas cleaning is involved as a process in the system. The requirements are given for suspended substances, Hg, Cd, Tl, As, Pb, Cr, Cu, Ni, Zn and dioxins and furans.

9.9.2.7 Modelling unusual emissions

As much as reasonably possible, measured emission values shall be taken into account. The Incineration Directive (2000/76/EC) (now included in the new Industrial Emission Directive 2010/75/EC) and the BREF give the minimum compliance limit requirements for all waste incineration plants (emission limit values). They give requirements as concentrations in the flue gas at defined conditions and in the wastewater. These requirements can be regarded as a worst-case for emissions to air from W-t-E plants, as they must be compliant with the related legislation. Whenever possible (but it is hard to find data), those emissions should be included in the analysis as they may generate a significant share of the emissions on an annual basis.

Conversely, actual emission values may be significantly lower than legal emission limits. For example, the dioxin emission limit is set at 0.1 ng/Nm³, whereas, many W-t-E plants do not exceed 0.01 ng/Nm³.

This underscores the following rationale: “whenever possible, **measured yearly average** should be considered as a reference for modelling instead of legal emission limits”.

9.9.2.8 Solid residues

Waste incineration produces various types of solid residues. As presented in the BREF document (2006), a distinction can be made between residues resulting from the:

- Incineration process itself, e.g., bottom ash, boiler ash, fly ash, slag, bed ash;

- Flue-gas Treatment (FGT) system, e.g., fine fly ash and/or reaction products and unreacted additives (often called Flue-gas Treatment (FGT) or Air Pollution Control (FGC) residues). They include fine fly ash, filter cake, sludge from scrubbers, excess lime and reaction products, gypsum, salts, etc.

The treatment/recycling method varies according to the type of residues. Their production and content is influenced by[111]:

- Waste content and composition. This affects the ash volume and composition, the volume of bottom ash produced and the chemistry of the flue-gas cleaning residues;
- Furnace design and operation. For example, pyrolysis plants deliberately produce a char in place of the ash, and higher temperature furnaces may sinter or vitrify the ash and volatilise some fractions;
- Flue-gas treatment design and operation. For example, some systems separate dusts from chemical residues, wet systems produce an effluent for treatment to extract solids.

Commonly, bottom ash is recovered and used as aggregate for road construction. Steel is also systematically extracted from bottom ash (with separation efficiency around 85-90%) and recycled. Non-ferrous (NF) metals may be extracted from bottom ash using Eddy currents. This extraction process is efficient mainly for extracting relatively pure, massive fragments; it has lower efficiency for lighter fragments because the attraction forces are not sufficient to lift both the non-ferrous metal and the other surrounding wastes (either dirt or other materials above the NF on the conveyer belt). Boiler ash, fly ash and epuration residues are generally stabilised and landfilled.

9.9.3 Modelling recommendations

9.9.3.1 Modelling vs. data base

When the environmental impacts of the W-t-E plant play a critical role in the results and the conclusions, standard values obtained from a database may not be appropriate and specific models should be applied to more accurately model the plant impacts (i.e., emissions to air, production of solid residues of different types, consumption of reactants and energy recovery).

9.9.3.2 Waste composition

The impacts of incineration are very sensitive to the waste composition. Thus, experts should strive to collect specific information about the composition in order to:

- Check whether it is close to the composition used to produce the life cycle inventory (LCI) from data bases. If it is close, LCI from data base can be used;

[111] BREF document (2006): Integrated Pollution Prevention and Control - Reference Document on the Best Available - Techniques for Waste Incineration - August 2006 - European Commission

- If it is not close, experts should model the environmental impacts, either completely or partly (e.g., only carbon content, calorific value and inert or chlorine content);
- It should be taken into account that different waste streams are evaluated (mixed waste, source separated waste) when comparing different treatment methods.

When comparing W-t-E to AD or composting processes, the evaluations should consider the same waste stream.

9.9.3.3 Energy recovery

Modelling energy recovery commonly requires a sophisticated modelling approach. The relative importance of incineration in the LCA should be directly reflected into the required sophistication of the model. Particular attention should be paid to:

- The definition of efficiency by data providers, e.g., whether the efficiency is based on the net or gross calorific value, and whether the efficiency is gross or net;
- The availability of a market/consumer for the heat. For example, if heat in only used to warm up houses, heat could be lost at summer periods. In this case a correction factor should be applied (fraction of the energy that is actually valorised);
- How the avoided energy is produced.

Annex C6 expands on assessing impacts and benefits of energy recovery. However, reference shall always be made to the ILCD Handbook[112].

9.10 Co-processing of waste in industrial processes

9.10.1 Overview

Co-processing is the use of waste as raw materials and/or as a source of energy to replace natural mineral resources and fossil fuels (coal, petroleum and gas) in industrial processes such as steel, aluminium, brick or cement. In this chapter the LCA guidance is illustrated for co-processing in a cement kiln: however, the concept should be similarly applicable to other resource-intensive industries.

The appropriate feeding point (place where the waste enters the kiln, i.e. either at the flame side, at cold side or mid-kiln) depends on the characterisation of the waste and the typical process conditions of each kiln and has to be well selected in order to comply with the emission limits as defined in the waste Incineration Directive (2000/76/EC). The efficiency and environmental performance of the kiln process itself is described in the BREF in the Cement, Lime and Magnesium Oxide Manufacturing Industries (BREF CLM, May 2010[113]).

[112] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, especially Chapter 7 and Chapter 14; http://lct.jrc.ec.europa.eu/publications

[113] http://eippcb.jrc.es/reference/

9.10.2 Key technical and modelling aspects

Some waste streams, such as waste tyres and foundry sand, are suitable for direct injection into the kiln system without any pre-treatment operation. Other waste streams, such as unsorted municipal solid waste (MSW), need a pre-treatment operation before they are suitable for co-processing. The environmental impacts associated with the pre-treatment operation should be included within in the system boundaries.

As described in the BREF CLMvarious kiln technologies exist within individual sectors or among the various industrial sectors. These technological differences may have a significant influence on the associated environmental impact indicators. Specific consideration of these technology-related specificities is necessary when conducting an accurate and representative LCA modelling work.

Waste pre-treatment operations can be very different depending on the type of waste stream being treated. The LCA assessment of the pre-treatment installations should focus on:

- Use of additives, such as saw dust for hazardous waste pre-treatment plants;
- Use of (primary) energy, which may be significant for drying and shredding operations;
- Emissions to air;
- Emissions to water;
- Type of residue requiring further treatment, recycling, other recovery or disposal;
- Transport and logistics of all incoming and outgoing flows.

Useful information regarding waste treatment can be found in the Reference Document on the Best Available Techniques for the Waste Treatments Industries[114].

Resource-intensive industries are capable of using waste as either:

- Alternative fuels;
- Or alternative raw materials (with the minerals being incorporated in the clinker matrix);
- Or both.

9.10.2.1 Primary fuel substitution

In addition to use as a substitute for primary fuels, the biomass content or the CO_2 emission per GJ of (alternative) fuel is an important indicator for comparing its impact on greenhouse gas emissions. The biomass content can either be measured or the content is determined by an authorised body for a certain category of alternative fuel. Cement plants have to report on the CO_2 emissions of their production process, including the use of (alternative) fuels. Authorisations, audits, etc., on CO_2 reporting are common practice within EU cement plants.

A major advantage of the energy recovery from waste in a cement kiln is that the minerals are recovered as raw materials. This therefore means a simultaneous recovery of energy and minerals.

[114] European Commission, 2005

9.10.2.2 Raw material substitution

Another important key indicator is the virgin raw material substitution. The raw materials in clinker manufacturing process consist of limestone and other correctives in order to have enough Si, Ca, Al and Fe available for sintering the required quality of clinker.

A special added value in terms of LCA, are those materials that have decarbonised CaO in their mineral fraction, since this avoids the release of the CO_2 that is unavoidable when turning limestone ($CaCO_3$) into clinker via a decarbonisation process ($CaCO_3 \rightarrow CaO + CO_2$). Therefore these materials avoid both the use of virgin raw material and the related CO_2 emissions. The modelling should include the waste preparation, as it is required by all these techniques, and the impacts connected to the combustion of chars or other so-called fuels.

9.10.2.3 Emissions to air

A cement kiln has base load emissions due to the physico-chemical reactions involving the raw materials and the combustion of fuels. These emissions have to be in compliance with the provisions of the IPPC Directive (which will become the Industrial Emissions Directive (IED) in the future).

When a cement kiln co-processes waste materials and/or waste derived fuels, then the additional requirements of the Waste Incineration Directive (WID) for co-incineration of waste are applicable.

The IPPC Directive includes a general indicative list of the main air-polluting substances to be taken into account, if they are relevant for fixing emission limit values. Those relevant to cement manufacture, including the use of waste, are:

- Oxides of nitrogen (NO_x) and other nitrogen compounds;
- Sulphur dioxide (SO_2) and other sulphur compounds;
- Dust;
- Total Organic Compounds (TOC) including volatile organic compounds (VOC);
- Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs and PCDFs);
- Metals and their compounds;
- Hydrogen fluoride (HF);
- Hydrogen chloride (HCl);
- Carbon monoxide (CO).

Exemptions for SO_2 and TOC are process related and not linked to the use of waste.

Table 10: Emission limits according to Waste Incineration Directive for cement kilns co-processing waste

Pollutant	**Co-processing waste in cement kilns** **mg/Nm^3 @ 10% O_2** *(Exemptions can be given by competent Authorities)*
Hg	0,05
Cd+Tl	0,05
Sum heavy metals	0,5

Dioxins/furans	0,1
HCl	10
HF	1
NO_x	500/800 (existing plants)
SO_2	50*
TOC	10*
Dust	30

For a comparative LCA, the delta emission is the key factor. So, the reference emission level of a cement kiln not using the specific waste material is to be compared with the new emission level when co-processing waste. Whenever possible, representative and accurate measures should be used Particular attention should also be paid to “mercury containing waste” and the LCA-analyst should note the management methods the specific cement plants are applying to control mercury inputs and emissions. In addition, the potential reduction of NO_x when burning a waste material (and thus reducing the flame temperature) should be weighted, or at least discussed, in an LCA comparison.

Emissions from cement plants are largely independent of the type of fuel used (major exception is CO_2), but depend predominantly on the natural raw materials and the process. Hence, no relevant increases in pollutant emissions to air will be observed when substituting fossil fuels, provided that the alternative fuels undergo a rigorous acceptance and inspection procedure before being used.

9.10.2.4 Emission to water

In general, cement production does not generate liquid effluent. In the same way, co-processing in a cement kiln does not generally generate any waste water; however, depending on the technology (e.g., semi-wet process) water treatment may be needed and should be included in the system boundaries. Water emissions occur during the waste preparation process (to transform it into a usable form).

9.10.2.5 Dust management

The exhaust gases of cement kilns are dedusted by bagfilters or ESPs (Electro static Precipitator). The dust from the bagfilters is added to the raw material and reprocessed in the clinker manufacturing line. Depending on the process requirements, a rotary cement kiln can be equipped with a by-pass installation, taking out a part of the exhaust gas between the rotary part and the preheater tower. The by-pass gas is rapidly cooled down to condense volatile elements such as alkalis and chlorines. Finally the gas passes through a dust collector. This dust is known as by-pass dust. The by-pass dust is usually added to the cement grinding section as a filler to the regular cement grades Dust management and treatment should be included in the system boundaries.

9.10.2.6 Consumption of chemical reagents

The exhaust gas cleaning in cement kilns does not normally use any reagents. In the calcination zone, the SO_2 and HCl are trapped due to the presence of CaO, whereas, the pre-heater acts as a multi-stage scrubber using the raw material powder as a process-integrated agent. Finally, the dust collector will collect the fine dust without any additional reagent. Those chemicals end up in the clinker and thus in cement.

The LCA analysis should confirm whether there is an impact on the amount of Denox reagents (usually it is lower) and if indeed no additional reagents are required to maintain the emission levels at the reference level.

9.10.2.7 Product quality assurance

Co-processing of waste materials implies that the material part of the waste is recovered within the clinker and finally within the cement. The cement, however, must still comply the cement standard EN 197-1.

The use of waste in the clinker burning process may change the metal concentrations in cement products. Depending on the total input via the raw materials and fuels, the concentration of individual elements in the product may increase or decrease as a result of waste processing. As cement is blended with aggregates, e.g., gravel and sand, for the production of concrete or mortar, it is the behaviour of the metals in the building material (concrete or mortar) which is ultimately decisive for evaluating the environmentally relevant impacts of using waste to fuel the clinker burning process. Metal emissions from concrete and mortar are usually low.

In this case, the use of waste has no negative impact on the environmental quality of the product. Under these conditions, cement can continue to be used without restrictions for concrete and mortar production. The recyclability of these materials remains unaffected.

9.10.3 Modelling recommendations

The table below provides an indication of the heat value before and after pre-treatment, and the biomass content of typical alternative fuel streams in the cement industry.

Table 11: Example waste streams mainly for energy recovery, secondary for mineral recovery: heat value, mineral fraction and biomass content.

Waste stream	Heat value at cement plant (GJ/t)	Valuable mineral content (main element + tot mineral %)	Biomass %
Waste tyres	approx 26	Fe, 10%	25 - 30%
Waste oil	25 - 36	< 2%	0%
Animal meal	14 - 18	Ca, 15 - 25%	100%
Sewage sludge	12 - 16	Si, 30 - 40%	100%
MSW	14 - 25	Ca, 10 - 15%	25 - 80%
Commercial/ industrial: plastic/paper/textile	17 - 40	Ca, 10 - 15%	5 - 50%

Impregnated saw dust	14 - 28	Si, 5 - 15%	15 - 60%

When the environmental impacts of the co-processing play a crucial role in the LCA results and conclusions, standard data available from the database might not be specific enough to evaluate the pre-treatment operations and the final co-processing operations. In that case, specific modelling should be performed.

The impacts of the co-processing are very sensitive to the waste composition. LCA-practitioners should strive to collect specific information about the composition in order to:

- Check whether it is close to the composition used to produce the LCI from databases. If it is close, LCI from databases can be used; if it is not close,
- LCA practitioners should model the environmental impacts, either completely or partly (e.g., only carbon content, mineral content or calorific value).

9.11 Alternative thermal treatments

9.11.1 Overview

A wide range of emerging thermal treatments exist for the treatment of municipal waste (not only bio-waste). **Pyrolysis** and **Gasification** are perhaps the most promising at this time.

Pyrolysis is a thermal process where the organic fractions in the waste are broken down the absence of oxygen and under pressure. The process efficiency increases for increasing content of carbon in the waste input. Like for the other thermal treatment technologies, it is important that the waste input is selectively collected, so that most of the non-organic components are removed and the waste is homogeneous. The Pyrolysis process produces both a liquid residue and gaseous output; the latter may be combusted to generate electricity. In addition, a solid char is produced which may require disposal (e.g., landfilling) or additional processing (e.g., gasification).

Gasification requires the addition of an oxidant (e.g., air or oxygen) and typically operates at a higher temperature than pyrolysis. The solid char output from a pyrolysis plant may be fed into the gasification process. Gasification of organic waste (e.g., bio-waste) generates a gas that can be burnt to generate electricity and a char. The latter may be used as secondary construction material, thereby, substituting virgin materials; if no markets are available, it usually requires disposal. It can also be used as as a soil amendment (e.g., *terre preta* of the Amazon) and carbon sink (generally stable for centuries).

These technologies still present technical challenges and are not as extensively applied as incineration or composting. Some are still in a pilot stage and experiences with large-scale facilities (e.g., with an annual capacity of ~10.000 tonnes) may be limited. Extensive and robust datasets on pyrolysis and gasification plants are, therefore, still limited. This limits extensive assessments of their actual environmental performance. However, pyrolysis and gasification of waste are expected to become more widely used in the future, as public perception of waste incineration in some countries is a major obstacle for installing new incineration capacity.

9.11.2 Key technical and modelling aspects

The same modelling approach as previously described for W-t-E plant shall be applied. Considering that these treatments are much less frequently applied to waste than waste in W-t-E plants, it could be difficult to obtained accurate process specific data or to apply a thorough waste specific approach. In this case, BAT data can be used. The environmental performance of the advanced thermal treatment depends on:

- The site's energy consumption;
- The efficiency of gas production and type of recovery.

For new plants, modelling should account for possibility of needed additional sub-treatment processes to improve the quality of the outputs and/or the lack of output markets. Variation of the overall process efficiency should be tested using sensitivity analysis.

The alternative thermal treatments are not widely applied to waste treatment. Therefore, LCA practitioners shall take precautions in conducting LCA studies on these waste treatment technologies, applying sensitivity analysis including lower efficiencies and concluding with the necessary reservations. Theoretical modelling must be performed in a conservative way.

9.12 Landfilling

9.12.1 Overview

With respect to waste landfilling, the reference European Directive is the so-called Landfill Directive (LD) (1999/31/EC)[115]. This directive aims at providing measures, procedures and guidance to avoid as much as possible the adverse environmental consequences from landfilling of waste throughout the life cycle of the landfill. In particular, pollution of surface water, groundwater, soil, air (including greenhouse effect), as well as any resulting risk to human health shall be avoided. The Landfill Directive recognises that a key source of potential environmental impacts is represented by the organic waste fractions landfilled. In response to this, the Landfill Directive establishes a progressive reduction of landfilling of biodegradable waste fractions in the Member States.

Conventional landfilling usually relies on anaerobic degradation of waste. Typical technical measures implemented include bottom and side liners, top soil cover, gas and leachate collection and treatment systems. These are kept active for at least 30 to 40 years.

New technologies aim at minimizing environmental impacts from conventional landfilling and at reducing the duration of active operations required at landfills to a maximum of 10-15 years. In addition, active landfill technologies often utilise the collected gas for electricity and/or heat generation, providing additional environmental benefits[116]. Biogas is only recovered in large landfills.

Figure 17 shows a simplified structure of the key parts that are usually considered when performing an LCA including the landfilling option.

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[115] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1999:182:0001:0019:EN:PDF

[116] Manfredi, S. & Christensen, T.H. (2009): Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management* 29, 32-43

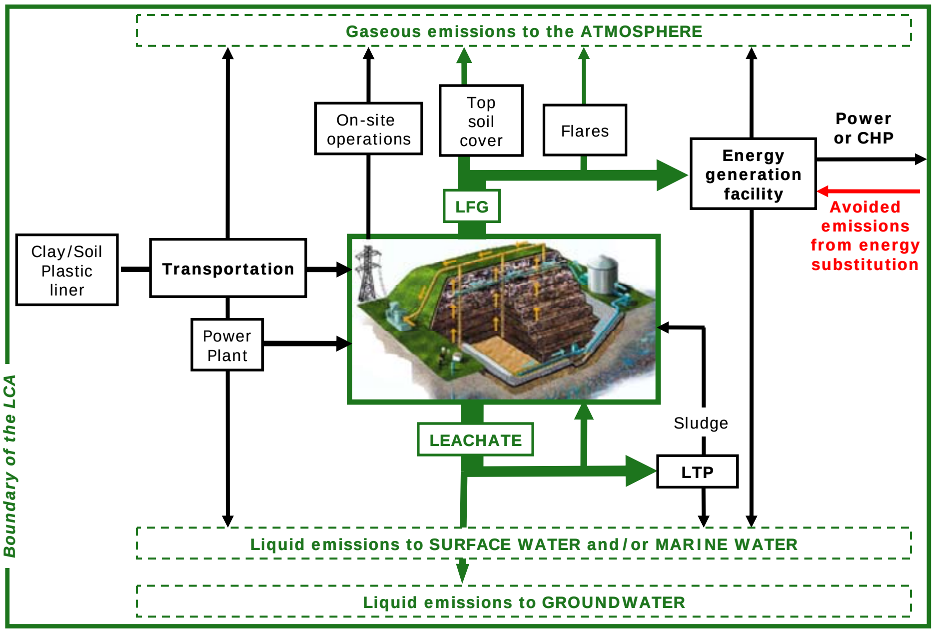

Figure 17: General structure of landfilling technologies and boundary of the assessment[117]

The overall environmental performance of a landfill site is highly variable and depends on the specific performance of the gas/leachate collection and treatment systems, emission levels, energy production efficiency, effectiveness of the barrier systems, etc. These specific factors depend on:

- Site settings: technology (open dump, conventional landfill, standard bioreactor landfill, flushing bioreactor landfill, semi-aerobic landfill, etc.);
- Operation: effectiveness of gas/leachate collection and treatment/utilisation;
- Waste composition: hemicellulose or cellulose content, metals, water content, proportion of inert materials, etc.

Data for landfilling a range of materials and mixed waste in different regions of Europe is included in the ELCD database[118].

9.12.2 Key technical and modelling aspects

[117] Adapted from Manfredi, S. & Christensen, T.H. (2009): Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management* 29, 32-43
[118] http://lct.jrc.ec.europa.eu/assessment/data

9.12.2.1 Time perspective[119,120,121,122]

Modelling landfills in an LCA perspective is challenging because of several specific issues. Emissions and energy recovery from a landfill may occur over a long period of time after waste delivery has been terminated. Gas extraction from a landfill with municipal waste may take place for 30–40 years after the landfilling has ceased, while leachate emissions from a landfill may potentially continue for several centuries. In contrast, emissions from treatment plants (e.g., incineration plants plants) occur within very short time frames (for example, within a month from receiving the waste).

For LCA modelling of landfills, the choice of suitable time horizon depends on several factors, including the availability and reliability of input data. In principle, it is important to select an LCA time horizon that is long enough to include all relevant emissions. This is practically hardly possible as data availability and quality decrease dramatically for increasing duration of the landfilling process.

Long-term emissions (i.e. emissions occurring beyond the selected time horizon, e.g. beyond 100 years from the year of analysis) are to be treated as separate inventory items from the emissions estimated to occur during the time horizon (e.g., within the first 100 years).

9.12.2.2 Representativeness

When modelling a landfill in LCA, it is usual to consider the modelling of a new landfill, so the emissions calculated by the LCA reflect only the waste deposited in the scope of the study. This is the right modelling when the building of a new landfill is envisaged as an alternative to the present management.

When the goal of the LCA study is to analyse the alternatives relative to the present waste treatment scheme (landfill used as reference system), the existing landfill should be considered, possibly with limited efforts to capture leachate and air emissions for proper treatment. Available data from literature and databases for landfill often relate to old landfills. The data needed depends on the goal of the study:

- If the LCA study compares alternatives to an existing landfill, then data referring to this (old) landfill (type) should be used. Data from databases are available;
- If an existing landfill is getting filled and an alternative is searched, including building a new landfill site, using modern techniques (membranes, capping, leachate and gas recovery and treatment, etc.), a modern landfill needs to be modelled and specific data sets should be searched.

Similarly, if the LCA study concerns a specific waste stream, specific data relating to this stream should be used. This means allocation of impacts among the different waste

[119] Manfredi, S. & Christensen, T.H. (2009): Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management* 29, 32-43

[120] Hauschild, M.Z., Olsen, S.I., Hansen, E. & Schmidt A. (2008): Gone…but not away – addressing the problem of long-term impacts from landfills in LCA. International Journal of Life Cycle Assessment, 8 (13), 547-554

[121] Hansen E., Olsen S.I., Schmidt A., Hauschild M., Hjelmar O., Bendtsen N., Poulsen T.S., Hansen H.H. & Christensen K. (2004): Life cycle assessment of landfilled waste (in Danish). Environmental project no. 971, Danish Environmental Protection Agency, Copenhagen, Denmark

[122] Environmental Assessment of Solid Waste Landfilling in a Life Cycle Perspective (LCA Model EASEWASTE), Simone Manfredi, PhD Thesis, June 2009, DTU, Department of Environmental Engineering

components is necessary. For example, if the goal of the study is to determine the benefits of selective collection of glass for recycling as an alternative to landfilling (in MSW), a specific modelling should not account for any air emissions as glass does not degrade at all.

If the waste deposited during the study time horizon and the historical waste are similar, available data from the historical waste can be used. Otherwise, study-specific modelling is necessary.

9.12.2.3 Influence of waste composition on emissions

Waste-specific data approaches take into account the initial waste composition. The causal relationship between the specific waste input and the resulting emissions is calculated by modelling. Some of these emissions directly depend on the chemical composition of the waste, whereas, others are process-dependent and may be difficult to predict. Different approaches can be used for modelling (presented below in increasing order of sophistication):

- To consider the theoretical maximum pollutant load, i.e., all pollutants contained in the waste are emitted, either to air or water;
- To calculate the behaviour of the target waste under physical-chemical conditions experienced at landfills, i.e., using modelling based on the degradability of waste fractions and distributions factors (among air emissions, water emissions and permanent residence in landfill);
- To perform model calculations using landfill-specific parameters. Different release factors are calculated for each chemical compound/element/constituent and these are calibrated based on field measurements. Uncertainties in chemical and biological interactions and the preferential flow of leachate through the landfill body make projections difficult, but these should also be considered. Only calibrated models should be applied.

9.12.2.4 Direct atmospheric emissions

When waste containing organic fractions is landfilled and undergoes degradation under anaerobic condition, landfill gas is produced. This is a mixture of mostly methane and carbon dioxide, though a variety of other compounds are found. In typical MSW landfills, an overall gas generation potential of about 150-200 m^3 per tonne of (wet) waste can be expected from waste degradation[123]. Most of this gas is generated during the initial 3 to 4 decades of degradation in conventional landfills. In bioreactor landfills, due to the optimised degradation environment, this reaction time is reduced to about 10-15 years.

During the period of massive gas generation, it is crucial to optimize the performance of the gas collection system and the utilisation/treatment systems, so that emissions to the environment are minimized. In addition, it is also important that a properly constructed top-soil cover is installed. In addition to protecting the landfill microbial environment and controlling water infiltration, a top-soil cover also facilitates oxidation of the uncollected gas

[123] This is intended as overall infinite potential for landfill gas generation, which corresponds to the volume that would be generated from anaerobic degradation of the entire waste carbon content. In practice, not all of this potential is generated.

(CH_4 to CO_2), thereby reducing the GHG load on climate change (as the climate change potential over 100 years of methane is 25 times higher than that of methane – IPCC 2006 4th Assessment Report).

Note: Monitoring of LFG extraction is very costly, so relatively few measurements have been made. Accordingly, great uncertainty exists around this issue, which is reflected in the large variation of extraction percentages reported by countries in the NIR (national inventory report) under the UNFCCC (United Nations Framework Convention on Climate Change).

Methane and Carbon Dioxide

Methane is linked to the anaerobic decomposition of waste by microbial populations. Unlike CO_2, it is considered as anthropogenic because the gas would not be emitted if waste was not landfilled. Only the fraction of carbon that is both bioavailable and biodegradable can potentially generate methane. This fraction is mainly composed of cellulose and hemicellulose. Conversely, the chemical structure of lignin, which is one of main constituents of plant cell walls, makes it highly resistant to microbial degradation and limits the bioavailability of other constituents of cell walls.

The key factors influencing the generation of landfill gas are:

- Waste composition, in particular content of organic matter;
- Microbial population;
- Nutrient availability;
- pH of the water phase;
- Water content (promotes exchanges between micro-organisms, nutrients and degradable substrates);
- Soil structure (calcareous soils limit acidification and are generally associated with higher CH_4 generation rates);
- Proportion of cellulose, hemicellulose and lignin.

It is important to use a waste-specific approach to estimate CH_4 and CO_2 generation. Methane released to the environment from anaerobic decomposition of biomass is not considered carbon-neutral.

Note: Carbon-neutral means that the net carbon captured and released by the biomass during its life and decomposition is null. This is not the case when biomass degradation produces CH_4, since CH_4 (released during plant degradation) has a Climate Change Potential that is 25 times higher than that of CO_2 captured during plant growth).

A portion of the landfill gas is often collected and combusted. The combustion transforms most of the CH_4 into CO_2. The proportion of landfill gas that is collected for proper handling needs to be carefully estimated. Estimates range from 20% to 80% of the total infinite potential for gas generation (approximately 150-200 nm^3 gas per tonne of MSW landfilled). Gas collection efficiency is a crucial parameter for the assessment. Therefore, great efforts should be spent for making the best estimate for this parameter through collecting data, modelling and performing adequate sensitivity analysis.

Concerning the inclusion of carbon form biogenic sources, see ILCD Handbook Chapter 7.4.3.7.

Nitrous oxide

Emissions of nitrous oxide (N_2O) from landfill sites are small and often neglected in LCAs. Nitrous oxide is the co-product of the nitrification and denitrification reactions. Small quantities may also be emitted when flaring biogas.

Other pollutants

Pollutants are emitted to air from landfills through direct evaporation from the landfill (e.g., N_2O, VOCs, H_2S, HCl, CFC, HCFC, other organic pollutants) and through combustion of landfill gas (CO, NO_x, SO_x, VOCs, PCBs, etc.). Although methane and carbon dioxide are the primary constituents, landfill gas typically also contains on the order of 120-150 trace components, which constitutes about 1% of the landfill gas volume. The wide range of trace compounds is mainly determined by the types of waste deposited. It is therefore preferable to apply waste specific models as a basis for estimating emissions to air from landfills.

Landfill gas combustion can be easily modelled. The key factors influencing the emission of landfill gas are:

- The area of the open surface;
- The time during which a cell is in operation without gas extraction system;
- The cover system;
- The biogas treatment system.

9.12.2.5 Emissions to water

The amount of leachate generation depends on climatic factors (e.g., precipitation and evapotraspiration), cover design and geometry of the landfill. The higher the waste thickness, the lower leachate generation rate per tonne of waste landfilled. Leachate composition depends on the type of waste landfilled, but not directly on the chemical composition of the actual waste. For example, the cadmium content of the leachate is not directly related to the amount of cadmium landfilled since it is the chemistry at the waste–leachate interface that governs the cadmium concentrations in the leachate. In particular, with respect to heavy metals concentrations, the pH is the single most important parameter. Leachate emissions depend on the efficiency of the leachate collection system and the performance of the bottom liner.

Modelling

Modelling leachate emissions from landfills requires:

- Selecting the period of time for which emissions shall be quantified (in line with the LCA time horizon, e.g., 100 years);
- Gathering data on leachate generation rates for all components for the selected time interval;
- Gathering data for the type and fraction of the pollutants removed by leachate treatment;

- Calculating emissions to the environment (e.g., g pollutant / kg waste) based on waste composition, leaching rates, leachate collection efficiency and removal efficiencies of leachate constituents at the treatment plant.

9.12.2.6 Impacts of the landfilling operation

In addition to impacts from emissions of gas and leachate, the landfilling process causes environmental burdens from on-site operation, e.g., specialised vehicles operating on-site. However, this typically constitutes a negligible impact.

9.12.2.7 Energy recovery

Gas collection and an overall good engineering of the landfill site enable gas utilisation for energy generation. The energy can be exploited as heat, electricity, combined heat and electricity, or collected and refined to substitute natural gas.

The main component of landfill gas is CH_4 (about 50% vol). As an approximation, it is common to assume that the energy recovery is related to CH_4 alone.

The energy recovered based on a waste-specific approach can be estimated from:

- The amount of CH_4 produced by the degradation of waste flow in question. This is calculated based on the waste composition as all waste fractions have their own specific CH_4 generation potential based on bio-available carbon and defined period of time where CH_4 generation takes place;
- The amount of CH_4 collected and effectively sent for treatment;
- The net heat value of CH_4;
- The efficiency of energy recovery/production process.

New landfills are usually required to have gas collection and flaring systems, while most old landfills lack such systems.

Modelling landfill gas valorisation requires either (preferably) a thorough analysis of the effective valorisation of outputs (preferable for existing plants) or a sensitivity analysis to show the effects of potential lack of output markets (new plants). Modelling energy recovery might require sophisticated modelling. The higher its importance in the LCA, the more sophisticated the modelling should be.

9.12.2.8 Carbon storage and delayed emissions

Carbon storage and delayed emission should be reported separately from the Climate Change results based on short-term emissions of greenhouse gases. By default they are <u>not</u> to be included in the analysis and in the recommendations, as required by the ILCD Handbook:

"*They require special or separate analysis only if such is included in line with an explicit goal requirement: Separately analyse and jointly discuss the results including and excluding carbon storage and delayed emissions / re-use/recycling/re-use credits*." [124]

See also ILCD Handbook:

- Chapter 7.4.3.7.3 "Temporary carbon storage, delayed greenhouse gas emissions, delayed credits for solving multifunctionality";
- Chapter 14.5.3.5 "Time aspects in “delayed” recycling of long-living products".

9.12.3 Modelling recommendations

9.12.3.1 Modelling vs. data base

When the environmental impacts of landfilling play a crucial role in the results and the conclusions, standard values from database may not be appropriate. Specific models should be applied to obtain a more relevant simulation of the emissions to air and water, and energy recovery from biogas combustion. When using available data, corrections are necessary to exclude emissions related to historical waste (i.e., waste deposited in the landfill in the past, thus, not the waste targeted in the study).

9.12.3.2 Time perspective

Emissions to air and leaching should be considered over the whole life of the landfill, i.e., during exploitation and after, when landfilled waste continues to react and to emit pollutants.

9.12.3.3 Land use and odours

Landfilling occupies space that is no longer available for other uses. Odours from landfills can be significant. Both impacts are difficult to model in LCA. However, they should be addressed, at least in a qualitative manner, in the analysis of the results to avoid the possibility that crucial impacts from landfilling are overlooked in the decision-making process.

9.13 Relative importance of life cycle stages

9.13.1 Transport and collection

Several LCAs show the influence of waste collection and transport on LCI results is relatively small in terms of energy demand and emissions of CO_2, SO_2 and NO_x. This conclusion appears for example in the LCA performed for the municipalities of Uppsala, Stockholm and Älvdalen[125].

[124] ILCD Handbook Provisions 9.4, p.304

[125] Municipal solid waste management from a systems perspective, O. Eriksson et al. (2005) Journal of Cleaner Production 13 (2005) 241–252

There are however exceptions (e.g., truck with small load, very long distances, transport by air, transport by individuals for bring systems, etc.), so, those stages should not be neglected *a priori*. Their influence on other impact categories might be significant. Specific health problems, such as cancer and respiratory diseases, may be significantly influenced by transportation.

Because transport/collection impacts are proportional to the distance driven, they correlate closely with cost figures. This stage, therefore, is very often "naturally" optimised (the environmental optimum is reached unintentionally because it coincides with the financial optimum) and is only very seldom a significant source of impacts or possible improvements.

Different from the – usually low – impact of collection and transport operations on the environmental performance of a solution, costs incurred by collection and transport operations are often significant and influence decision-makers. The additional cost of selective collection is much smaller when it allows lowering the collection frequency of the residual stream (i.e., the number of collection trips is constant).

9.13.2 Recovery processes

Generally, when there is a recovery process involved, the main source of (favourable) impacts is the avoided production process (e.g., electricity production in case of energy recovery, PET production in case of PET bottle recycling, etc.). It is therefore a fundamental requirement to apply a sophisticated modelling to determine which production process(es) are really involved and how much is avoided. The impacts of treatment and recycling processes are highly variable:

- Mechanical sorting processes are frequently a negligible source of impacts, but their efficiency is key because this determines the amount of material that can be valorised;
- With regard to overall waste, treatment processes (incineration, landfilling, etc.) are frequently a major source of impacts (e.g. greenhouse gas emissions, etc.);
- Recycling processes are of two types. "Cold" processes including cleaning and purification, are a source of water pollution and may consume some chemical reactants for the treatment. "Hot" processes are intended to produce the directly usable material such as glass and steel. Hot processes consume a significant amount of energy when the fusion temperature is high (e.g., glass, steel, aluminium). Fusion of plastics occurs at lower temperatures and requires less energy.

9.13.3 Iterative approach

An LCA should use an iterative approach to minimize the data collection and modelling work. In the first iteration, impacts are roughly approximated, with reasonable estimates plus reasonably worst-case scenario. In a second (and some cases third) step, this life cycle stage is refined, only if necessary and only if the real potential maximum influence of a parameter is high.

Annex A – Non exhaustive list of key definitions

The following table (adapted from ILCD Handbook[126] – General guide for Life Cycle Assessment – detailed guidance, Chapter 3) provides some key definitions in the context of Life Cycle Thinking and Assessment. However, this should not be intended as an attempt to provide an exhaustive glossary of relevant terms in LCT and LCA.

Table 12: Key definitions in the context of Life Cycle Thinking and Assessment

Term	Definition
Specific data	A specific data set in its pure form represents a single process (e.g., a specific technology as operated on a given site). It exclusively contains data that have been measured at the represented process.
Average data	An average data set ideally combines different specific data sets and/or other average data in an averaging way to represent a combination of processes (e.g., different waste incineration technologies). The averaging can - among others - go across technologies, sites, countries, and/or time.
Generic data	A generic data set has been developed using, at least partly, other information than those measured for the specific process. This other information can be calculation models, patents and other plans for processes, expert judgement etc. Generic processes can aim at representing a specific process or an average situation. Both specifically measured data and generic data can be used for the same purpose of representing specific or average processes or systems.
Technological representativeness	Degree to which the data set reflects the true population of interest regarding technology, including for included background data sets, if any.
Time-related representativeness	Degree to which the data set reflects the true population of interest regarding time / age of the data, including for included background data sets, if any.
Geographical representativeness	Degree to which the data set reflects the true population of interest regarding geography, including for included background data sets, if any.
Allocation [or: Partitioning]	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. [Source: ISO 14044:2006]
Analysed decision	Decision that is subject to an LCA.
Assumption scenario	Scenario for the analysed process or system that varies data and method assumptions with the purpose of evaluating the robustness of the study results and conclusions. If more than one alternative system or option are compared, each of them would have its own assumption scenarios.
Attributional modelling [or: descriptive, book-keeping]	LCI modelling frame that inventories the inputs and output flows of all processes of a system as they occur.
Co-function	Any of two or more functions provided by the same unit process or system.
Co-product	Any of two or more products coming from the same unit process or system. [Source: ISO 14044:2006]
Comparative assertion	Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. [ISO 14040:2006, ISO 14025:2006]
Comparative life cycle assessment	Comparison of LCA results for different products, systems or services that usually perform the same or similar function.
Consequential	LCI modelling principle that identifies and models all processes in the

[126] Available online at http://lct.jrc.ec.europa.eu/publications

modelling	background system of a system in consequence of decisions made in the foreground system
Disclosed to the public	The audience is not specifically limited and hence includes non-technical and external audience, e.g., consumers.
End-of-life product	Product at the end of its useful life that will potentially undergo re-use, recycling, or recovery.
Environmental impact	Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g., emissions, resource extraction, land use).
Functional flow	One of the (co-)product flow(s) in the inventory of a process or system that fulfils the process' / system's function See also: Non-functional flow
Mono-functional process	Process or system that performs only one function.
Non-functional flow	Any of the inventory items that are not (co-)product flows. E.g., all emissions, waste, resources but also input flows of processed goods and of services.
Multi-functional process	Process or system that performs more than one function. Examples: Processes with more than one product as output (e.g., NaOH, Cl_2 and H_2 from Chloralkali electrolysis) or more than one waste treated jointly (e.g., mixed household waste incineration with energy recovery). See also: "Allocation" and "System expansion"
Life cycle inventory (LCI) data set	Data set with the inventory of a process or system. Can be both unit process and LCI results and variants of these.
Life cycle inventory (LCI) study	Life cycle study that provides the life cycle inventory data of a process or system.
Life cycle inventory analysis results (LCI results)	Outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment. (Source: ISO 14040)
Overall environmental impact	Total of impacts on human health, natural environment and resource depletion for the considered impact categories. It can be calculated either as normalised and weighted overall LCIA results of the analysed process / system, or assuming an even weighting across impacts, i.e., for each and any of the impact categories.
Product	Any good or service; by definition a product is not (yet) a waste and a waste is not (anymore) a product. See "System".
Relevant	For LCI data sets: Having a significant influence on or contribution to the overall environmental impact of the analysed process or system, resulting in a different quality level. For LCAs: Having a significant influence on or contribution to the overall environmental impact of the analysed process or system, resulting in different conclusions or recommendations.
Substitution	Solving multifunctionality of processes and products by expanding the system boundaries and substituting the not required function with an alternative way of providing it, i.e., the process(es) or product(s) that the not required function supersedes. Effectively the life cycle inventory of the superseded process(es) or product(s) is subtracted from that of the analysed system, i.e., it is "credited". Substitution is a special (subtractive) case of applying the system expansion principle.
System	Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analysed in the context of the LCA. Note that ISO 14044:2006 generally refers to "product system", while broader systems than single products can be analysed in an LCA; hence

	here the term "system" is used. In many, but not all cases, the term will refer to products, depending on the specific study object. Moreover, as LCI studies can be restricted to a single unit process as part of a system, in this document the study object is also identified in a general way as "process / system"
System expansion	Adding specific processes or products and the related life cycle inventories to the analysed system. Used to make several multifunctional systems with an only partly equivalent set of functions comparable within LCA.
Unit process	Smallest element considered in the life cycle inventory analysis for which input and output data are quantified. (Source: ISO 14040) In practice of LCA, both physically not further separable processes (such as unit operations in production plants) and also whole production sites are covered under "unit process." See also "Unit process, black box," "Unit process, single operation." and "System."
Unit process, black box	A unit process that includes more than one single-operation unit processes.
Unit process, single operation	A unit process that cannot be further sub-divided into included processes.

Annex B – LCA step-by-step

This annex gives a very rough overview of what it means to perform an LCA study. It neither can nor is intended to replace expertise or a textbook/handbook. It expands on the information provided in Chapter 6 and builds on the ILCD Handbook[127] "General guide for Life Cycle Assessment – Detailed guidance". It is intended to provide a condensed overview of the steps. However, following this step-by-step guide cannot guarantee developing an ILCD-compliant study; for this the provisions of the ILCD Handbook should be applied.

B1. Goal definition – Identifying purpose and target audience

As the first phase on any LCA, the goal definition[128,129] is meant to identify the decision-context(s) and the intended application(s) of the study; therefore, it exerts a decisive influence on all subsequent phases, including a correct interpretation of the final results of the LCA. The following sub-chapters expand on the key aspects of the LCA goal definition.

Intended applications of deliverables and results

The intended applications of results shall be stated in a transparent, straightforward and unambiguous manner, so that misleading interpretations are avoided. Within the waste management context, the frequent applications include, but are not limited to:

- Comparison amongst alternative treatment options for a given waste stream
- Quantification of the environmental benefits arising from implementation of new waste management strategies, policies, technologies, etc.
- Identification of Key Environmental Performance Indicators (KEPI), i.e. those factors and parameters that most influence the environmental performance, as input to waste-type specific guides, or for deriving Ecolabel and Ecodesign criteria.

Method, assumption and impact limitations

The goal of the study can sometimes imply that limitations exist to the usability of the LCA results. These shall be clearly stated and subsequently reported. Often the limitations need to be adjusted or expanded during the course of the study. Limitations may be caused by the applied methodology, assumptions made or limited impact-coverage. An example of impact-coverage related limitations is the case of Carbon footprint calculations where exclusively climate change related greenhouse gas emissions are considered. Such an initial limitation can be fully justified, if the overall environmental impacts of the analysed product (and its competing products) are by far dominated by climate change impacts or if all other individually relevant impacts such as eutrophication and acidification are very closely and

[127] Available online at http://lct.jrc.ec.europa.eu/publications
[128] ISO 14044:2006 Chapter 4.2.2, http://www.iso-guidelines.com/
[129] ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance", Chapter 5, http://lct.jrc.ec.europa.eu/publications

positively correlated with climate change. Otherwise, such limitations in the initial settings can result in inadequacy for comparisons.

A common methodological limitation is that related to the use of average, site-unspecific data in LCAs that are aimed at informing a decision on a specific site. Limitations may also arise when assumptions are made on the characteristics of the analysed system or on specific scenarios that are uncertain and/or hard to verify. The extent to which the assumptions made influence the results of the study shall be systematically quantified during the interpretation of results.

Reasons for conducting the study and decision-context

Drivers and motivations for undertaking the LCA shall be made explicit and the decision-context shall be identified. The latter is one of the most important factors influencing the choice of the most appropriate method for the LCI modeling (i.e., “attributional” or “consequential”) and the related LCI method approach (“allocation” or “substitution”) that can also be applied in a systematic way, balancing theoretical exactness and practicality, as done in the ILCD Handbook. However, very often not only one method is appropriate (“attributional/consequential, allocation/substitution, etc.) and sensitivity analyses are necessary to test the robustness of results by comparing alternative substitutions or allocation criteria. More detailed, waste-specific guidance on how to identify the decision-context are given in Chapter 8.2 of this document.

The decision-context also directly determines other key aspects of the scope definition, the decisions to be made during inventory data collection and modelling, the calculation of impact assessment results, and, for LCAs, the LCA results interpretation.

Target audience

The goal definition shall also identify to whom the results of the study are directed, i.e., the target audience. Different types of target audiences (e.g., “internal” vs. “external” and “technical” vs. “non-technical”) typically imply different scoping requirements on documentation, review, confidentiality and other issues that are derived from the audiences” needs. For LCA applied to the waste management context, typical target audiences include amongst others waste policy-makers at European, national or local levels, waste managers, citizens (e.g., to promote in-house separate collection or advise on home-composting).

Comparisons intended to be disclosed to the public

The goal definition shall furthermore explicitly state whether the LCA includes a comparative assertion intended to be disclosed to the public[130,131]. This aspect entails a number of

[130] The ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance”, Chapter 6.10.1 (http://lct.jrc.ec.europa.eu/publications) defines “comparative assertion” as assertions that, based on LCA analysis, claim the superiority, inferiority or equality of alternatives. The addition “disclosed to the public” means that these conclusions of superiority or equality are published to the general public (i.e., are made available outside a small and well defined list of actors that were involved in the LCI/LCA study).

[131] All provisions of the entire ILCD Handbook refer to external use only. In-house decision support by LCA may draw on them but is outside any ruling, of course. "Disclosed to the public" refers here to the accessibility of the study or any of its

additional mandatory requirements under ISO 14040 and 14044 on the execution, documentation, review and reporting of the LCA due to the potential consequences the results may have for external companies, institutions, consumers, etc.

To avoid comparisons that want to lead the reader to a specific conclusion (e.g., by showing the numbers or graphics of the environmental performance of the compared systems without explicitly making an assertion as to superiority or equality), also comparative but not assertive LCAs shall meet these requirements, as far as applicable[132]. Note that "comparison" here refers to a comparison between systems (e.g., waste management systems), but not within a single system (i.e., not to a contribution or weak point analysis).

Commissioner of the study and other influential actors

The goal definition shall also identify the commissioner of the study as well as specify all financing and other organizations that have any relevant influence on the study, including other experts who may have been involved in the work.

results, conclusions, or recommendations to an audience outside the commissioner of the study, the involved experts, and any explicitly and individually named limited audience (e.g., an identified list of suppliers, customers, etc.)

[132] "applicable" means all requirements except for those that relate to the not covered parts: For product comparisons without conclusions and recommendations, the assertion-related provisions do not apply / cannot be applied. For LCI data sets all provisions that relate to the comparison do not apply / cannot be applied, as the comparison is done in the subsequent, external use of the LCI data set.

B2. Scope definition – What to analyse and how

During the **scope definition** phase[133,134] the object of the LCA (i.e., the exact system(s) to be analysed) is identified and defined in detail. This shall be done in line with the goal definition. The main part of the scope definition is to derive the requirements on methodology, quality, reporting, and review in accordance with the goal of the study, i.e. based on the reasons for the study, the decision-context, and the intended applications. The following sub-chapters expand on the key aspects of the LCA scope definition.

Defining the functional unit

A key aim of the scope definition is to define the "**functional unit**", i.e., the function or the service that the analysed system provides. The functional unit moves along questions such as "what", "how much", "how well", and "for how long". The function is thus characterised in qualitative terms, quantitative terms, and also the duration of the service provided is to be specified. Once the functional unit has been clearly defined, this can be transposed into the so-called "**reference flow.**" This represents the flow to which all other input and output flows quantitatively relate.

The duration of the service provided (identified by the functional unit) should not be confused with the **time horizon** of the LCA. The time horizon expresses the time length during which all the environmental aspects (e.g., inputs and outputs) are accounted for. The required time horizon to capture all significant emissions depends, amongst others, on the waste management options to be evaluated. For instance, while an incineration a time horizon of 20 years would cover most relevant emissions, landfills usually require longer time horizons. Generally, and as required by the ILCD Handbook, all emissions that occur within the first 100 years after the study are considered by default. Emissions that occur in the longer-term are to be inventoried as separate flows and also interpreted separately. This accounts for the inherently different certainty associated with certain time-dependent predictions, e.g., TOC emissions from landfill over a 10,000-year period compared to those in the first 10 to 20 years.

Solving multifunctionality

When conducting comparative LCAs, special attention shall be paid in the definition of the functional unit for each system compared. In principle, a fair comparison is possible only if all systems compared have the same functional unit. In practice this rarely happens due to the existence of co-functions in addition to the main function provided by the system(s) considered. If a process provides more than one function, i.e., delivering several goods and/or services (often also named simplified "co-products"), it is called "multifunctional." For instance, in case of incineration of MSW with energy recovery (in the form of electricity), in addition to the main function of providing treatment to the waste (i.e., waste incineration), the co-service "electricity generation" should be considered and properly accounted for.

[133] ISO 14044: 2006 Chapter 4.2.3, http://www.iso.org/iso/home.html
[134] ILCD Handbook, "General guide for Life Cycle Assessment – Detailed guidance," Chapter 6, http://lct.jrc.ec.europa.eu/publications

The choice of the proper mechanism to solve (account for) **multifunctionality** and thus render comparable functional units is to be made in accordance with the goal of the LCI/LCA and depends on the LCI modelling principle adopted.

The first choice is always to sub-divide the multifunctional process/plant data, i.e., aiming at collecting data for single processes that have no multi-functionality. As this is often not possible, including in co-incineration of different waste streams with the waste treatment of the different wastes being the main co-functions, other approaches need to be applied. Such a subdivision can however also be done based on other available information that allows separating the inventory into the different, waste streams. Note that this step is in fact identical to physical causality allocation.

Two main LCI modelling principles exist that follow different alternative steps for solving multi-functionality: **attributional** and **consequential**. Purely attributional LCAs apply “allocation” to solve multifunctionality when they are not interested to include existing interactions with other systems; otherwise they use “substitution / system expansion”. Consequential LCAs apply “substitution / system expansion” (see Annex C).

Defining system boundaries and cut-offs

The **system boundaries** define which parts of the life cycle and which processes belong to the analysed system, i.e., they are required for providing its function as defined by its functional unit. System boundaries separate the analysed system from the rest of the technosphere. System boundaries also define the boundary between the analysed system and the ecosphere, i.e., define across which boundary the exchange of elementary flows with nature takes place. A precise definition of the system boundaries is important to ensure that all attributable or consequential processes are actually included in the modelled system and that all relevant potential impacts on the environment are appropriately covered.

In attributional modelling the life cycle of the system is modelled as it is, following general supply-chain logic. The principle system boundaries and included life cycle stages can be derived from the goal and scope of the work. In consequential modelling, in contrast, the consequences that the decisions on the foreground system's processes of the analysed system exerts on its background system and/or other systems are modelled. In consequence, processes of other systems than the one analysed are to be included in the system boundary of the analysed system. The system boundaries of an identical product can differ markedly between these two modelling principles.

In both cases it is important that the life cycles of alternatives are comparable regarding their completeness of activities, life cycle stages covered etc.

In principle, all processes and flows that are attributable to the analysed system (or affected via consequences, in case of consequential modelling) are to be included in the system boundaries. However, not all these processes and elementary flows are quantitatively relevant; for the less relevant ones, data of lower quality ("data estimates") can be used, limiting the effort for collecting or obtaining high quality data for those parts. Among these, the irrelevant ones can be entirely **cut-off**[135]. Equally, if data of only very low quality is available, i.e., below data estimate quality, the data gap is to be reported as well (and the

[135] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance,” Chapter 6.6, http://lct.jrc.ec.europa.eu/publications

resulting lack of completeness to be reported and considered in interpretation). The reason for this is to avoid increasing the overall uncertainty by using low quality data. This is viewed by some to be less suitable than considering the data gap in the interpretation.

Cut-offs can be quantified in relation to the approximate percentage of environmental impacts that is to be excluded via the cut-off (e.g., "95%" relates to cutting off about 5% of the total environmental impact, or of a selected impact category). Obviously, it requires an approximation to know what is the 100% impact, because if one knew the total impact exactly, there would be no need for a cut-off. But the total inventory is always unknown for all life cycle approaches - the 100% always need to be approximated and extrapolated from the measured or calculated data. Other criteria than the environmental impacts may be used to approximate the cut-offs during the process, such as mass, energy and costs, while the quantitative measure always needs to relate to the impact coverage.

Dealing with data quality and data types

During the initial scope definition and in preparation of the subsequent work, the main types and sources of data and other information should be identified. These data types and sources will be more detailed and, frequently, will also be revised during the iterative steps of inventory data collection and modelling, impact assessment, and interpretation. For identifying the data and information needs and suitable sources, the required overall **data quality** is the key measure. This can be derived directly or indirectly from the goal of the LCI/LCA. Data quality is comprises accuracy (i.e., representativeness, methodological appropriateness and consistency), precision / uncertainty and completeness of the inventory. For an LCA, two types of data are usually required:

- Specific inventory data on the one or more processes to be developed in the foreground system;
- Average or generic (for attributional modelling) or (a mix of) marginal processes (for consequential modelling) for the background system.

It is important that all foreground and background data used in a LCI/LCA are methodologically consistent and that the overall quality requirements for the analysed system are met.

Review

It is useful during the scope definition to decide whether a **critical review**[136,137] will be done, and, if so, which form of review. This early decision will allow the data collection, documentation and reporting of the LCI/LCA to be tailored to meet the requirements of the review, typically shortening and lowering the overall effort.

Reporting

[136] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance,” Chapter 11, http://lct.jrc.ec.europa.eu/publications
[137] ILCD Handbook, “Review schemes for Life Cycle Assessment,” http://lct.jrc.ec.europa.eu/publications

Unbiased and transparent **reporting** is a vital element of any LCA. Without clear and effective documentation to experts and communication to decision makers, LCAs can be subject to erroneous and misleading use and, therefore, may not contribute to improving environmental performance. Reporting shall be objective and transparent; confidentiality concerns are addressed by reporting confidential information separately and making it accessible only to the reviewers under a formal confidentiality agreement. Generally, there shall be a clear indication of what has and what has not been included in the study, and what conclusions and recommendations the outcome of a comparative study supports and what not. The form and levels of reporting depend primarily on three factors:

- The type of deliverable(s) for the study;
- The purpose and intended applications of the study and report;
- The target audience (especially with regard to technical or non-technical and internal or third-party/public).

This ensures that the critically required documentation will be collected throughout the project.

B3. Life Cycle Inventory (LCI) – quantification of resource consumption and emissions

During the life cycle inventory phase[138], the actual data collection and modelling of the system (e.g., product) is done. These are performed in accordance with the goal definition and meeting the requirements specified in the scope phase. The LCI results are the input to the subsequent LCIA phase. The results of the LCI work also provides information to help reassess the the adequacy of scope phase since initial scope items frequently require refinement.

Typically, the LCI phase (data collection, acquisition, and modelling) requires the greatest effort and resources of the LCA process. The specific LCI tasks must be tailored to the study deliverable; not all of the following steps are required for all studies. In its entirety, life cycle inventory work means:

- Identifying the processes that are required for the system: different methods exist to identify processes within the system boundary, depending on the modelling principle that will be used (attributional or consequential);
- Planning collection of the raw data and information, and of datasets from secondary sources;
- For the foreground system, collecting unit process inventory data for the relevant processes. An important aspect is the interim quality control and how to deal with missing inventory data;
- Developing generic LCI data, especially where average or specific data are not available and cannot be developed, typically due to restrictions in data access or budget;

[138] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance,” Chapter 7, http://lct.jrc.ec.europa.eu/publications

- Obtaining complementary background data as unit process or LCI result data sets from data providers;
- Averaging LCI data across processes or products, including for developing production, supply and consumption mixes, in accordance with the goal and scope of the study;
- Modelling the system by connecting and scaling the data sets so that the system is providing its functional unit;
- Solving multifunctionality of processes in the system (Annex C);
- Calculating LCI results, i.e., summing all inputs and outputs of all processes within the system boundaries. The resulting inventories only include elementary flows that, in case of lack of a generally accepted methodology (like for example radioactive waste flows), need to be considered separately in the interpretation, e.g., as inventory category.

Data collection

Two types of inventory are usually required for an LCA:

Specific, **primary data** (input materials, energy, water, chemicals, wastes, wastewater and gaseous emissions) for activities in the "**foreground"** system. These include those under your direct control or decisive influence, e.g., on-site separation activities, logistical collection arrangements, and reprocessing operations; and

Non-specific, **secondary** data for activities in the "**background"** system, ie., those processes that are not under your direct control or decisive influence, such as diesel production for operating waste collection trucks and the avoided production of primary materials that are replaced by recycling. Typically, life cycle inventory databases provide ready-made datasets with the inventory of emissions and resources consumed (e.g., for producing electricity, virgin materials and other intermediate goods and services) are used for the background system. These can be based on "generic" or "market average" activities.

The upcoming ILCD Data Network is intended to provide a global network of quality-assured and consistent data sets from all interested providers with data that meet the minimum requirements. The ELCD database provides free-of-charge access to such data from EU level industry associations and other sources. Many of these data sets are independently, externally reviewed.

There are many other databases and tools available to support LCA studies. The European Platform on LCA (EPLCA) provides a comprehensive list in its Resource Directory (see http://lct.jrc.ec.europa.eu). Use of ILCD-compliant sources or data coming from the ELCD is preferred, if available.

Compiling a Life Cycle Inventory

The life cycle inventory is a "balance sheet" of material and energy inputs and emissions associated with each of the alternatives examined in the study. It is typically the first output of the modelling process, and it is the input for the subsequent impact assessment phase.

The life cycle inventory can be generated from a dedicated LCA tool (either application/topic specific, or a general tool), or it can be compiled from multiple specific tools (for instance transport model, process model, landfill emissions model, etc.) and then combined in a general LCA tool.

⇒ The ILCD handbook – General guide[139] contains more detail on inventory analysis and data collection procedures.

B4. Life Cycle Impact Assessment (LCIA) – quantification of environmental impacts

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inputs and outputs of elementary flows collected and reported in the inventory are translated into impact potential indicator results related to human health, natural environment, and resource depletion[140,141,142]. LCIA consists of mandatory steps (classification and characterisation) and optional steps (normalisation and weighting). The following sub-chapters expand on these aspects.

Mandatory steps: classification and characterisation

Based on **classification** and **characterisation** of the individual elementary flows (usually done by LCIA experts who provide complete sets of LCIA methods for use by LCA practitioners[143]), the LCIA results are calculated by multiplying the individual inventory data of the LCI results with the characterisation factors.

Classification involves assigning the elementary flows to the one or more relevant categories of impact. It involves a linear multiplication of the individual elementary flows with the relevant impact factors (i.e., characterisation factors) from the applied LCIA method. The **characterisation factors** express the individual contributions to the impact factor of each elementary flow relative to a reference elementary flow (e.g., the characterisation factor of methane (CH_4) for the impact category climate change over 100 years (GWP100) is equal to 25 kg CO_2-equivalent).

As the LCIA results per impact category have different units and scopes, they cannot be compared directly to identify which are most relevant. Similarly, they cannot be summed.

Optional steps: normalisation and weighting

[139] http://lct.jrc.ec.europa.eu/assessment/projects
[140] Reference to ISO 14044:2006, chapter 4.3.3
[141] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance,” Chapter 8, http://lct.jrc.ec.europa.eu/publications
[142] The ILCD handbook provides a list of recommended impact categories. Reference shall be made to: International Reference Life Cycle Data System (ILCD) Handbook - Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in a European context. Publications Office of the European Union; in publication, 2011. Will be available online at http://lct.jrc.ec.europa.eu/assessment/projects
[143] ILCD Handbook, “Framework and requirements for Life Cycle Impact Assessment (LCIA) models and indicators,” http://lct.jrc.ec.europa.eu/publications

Normalisation is a subsequent, optional step in which the LCIA results are multiplied with **normalisation factors** that represent the overall inventory of a reference (e.g., a whole country or an average citizen); the product is a dimensionless, normalised LCIA results. Normalised LCIA results provide for each impact topic or area of protection the relative share of the impact of the analysed system of the total impact of this category per affected population (e.g., per average citizen or globally, per country). When displaying the normalised LCIA results of the different impact topics next to each other, it becomes evident which impact categories the analysed system affects most, and least.

Normalised LCIA results reflect only the contribution of the analysed product to the total impact potential, not the severity/relevance of the respective total impact. Therefore, also the normalised LCIA results must not be summed.

Weighting is another optional step. In contrast to the preceding natural sciences-based phases, it includes value judgements. LCIA results (eventually normalized) are multiplied by a set of weighting factors, which indicate the different relevance that the different impact categories or areas-of-protection may have. Weighted LCIA results can be summed to obtain a single-value overall impact indicator. Weighting allows for directly comparing, or summing, results across categories or areas of protection; whereas, this cannot be achieved using natural-science approaches.

The decision of inclusion/exclusion of normalisation and weighting and related method details shall have been made and documented in the initial scope definition. In comparisons without normalisation and weighting, the LCIA results of the different impact categories or damages/areas-of-protection may point to different directions. However, if the study is intended to support a comparative assertion to be disclosed to the public, publication of numerical, value-based weighting of the indicator results is not permitted, in accordance with ISO 14040 and 14044[144].

For in-house purposes, the use of normalisation and weighting – preferably using several different approaches and value perspectives - can help demonstrate the robustness of the analysis. In contrast, if all impact indicators point into the same direction, the LCIA results can be the basis for interpretation phase of the LCA, including for comparative studies, clearly identifying a superior alternative (or, in case of limited significance of the differences, identifying equality of the compared alternatives).

[144] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54808

B5. Interpretation of results

The interpretation phase of an LCA has two fundamentally different main purposes:

- During the iterative steps of the LCA the interpretation phase serves to steer the work towards improving the Life Cycle Inventory model to meet the needs derived from the study goal;
- In the interpretation phase the results of the LCIA are appraised in order to answer questions posed in the goal definition. The interpretation relates to the intended applications of the LCI/LCA and is used to derive robust conclusions to develop recommendations.

The interpretation proceeds through three activities:

1. ***Identification of significant issues***[145]

The purpose of this first element of interpretation is to analyse and structure the results of earlier phases of the LCI/LCA in order to identify the significant issues. These can be among the following:

- Inventory items: main contributing “key” life cycle stages, processes, waste and elementary flows, parameters;
- Impact categories: main contributing “key” impact categories, which can be identified only if weighting was applied;
- Modelling choices and method assumptions: relevant modelling choices, such as applied allocation criteria / substitution approaches in the inventory analysis, assumptions made when collecting and modelling inventory data for key processes and flows, selecting secondary data, systematic choices on technological, geographical, and time-related representativeness, methodological consistency, extrapolations, etc;
- Commissioner and interested parties: the influence of the commissioner and interested parties on decisions in goal and scope definition, modelling choices, weighting sets, etc. Discuss their influences on final results and recommendations.

2. ***Evaluation***[146]

The evaluation element establishes the foundation for subsequently drawing the conclusions and provides recommendations during the interpretation of the LCI/LCA results. The evaluation is performed in close interaction with the identification of significant issues in order to determine the reliability and robustness of the results. The evaluation builds upon the results of the earlier phases of the LCA and analyses the LCI/LCA in an integrated perspective, i.e., based on the outcome of the inventory data collection, inventory modelling, and impact assessment. It is performed in accordance with the goal and scope of the LCI/LCA, and it involves three levels of checks:

- Completeness check on the inventory: this is done to determine the degree to which the inventory is complete and whether the cut-off criteria have been met;

[145] Refers to ISO 14044:2006 chapter 4.5.2 and to aspects of 4.4.4
[146] Refers to ISO 14044:2006 chapter 4.5.3

- Sensitivity check: it has the purpose of assessing the reliability of the final results and of the conclusions and recommendations derived. Scenario analysis and uncertainty calculations are the quantitative methods to support the sensitivity check. It is useful to structure the sensitivity check along the LCA phases “goal and scope,” “life cycle inventory,” and “life cycle impact assessment,”
- Consistency check: it is performed to investigate whether the assumptions, methods, and data have been applied consistently throughout the LCI/LCA in terms of accuracy, completeness and precision -. The consistency check applies to both the life cycle of an analysed system and between compared systems;

3. ***Conclusions, limitations and recommendations***[147]

Integrating the outcome of the other elements of the interpretation phase, and drawing on the main findings from the earlier phases of the LCA, the purpose of the final element of the interpretation is to draw conclusions and identify limitations of the LCA, and to develop recommendations for the target audience in accordance with the goal definition and the proposed applications of the results.

The conclusions should be drawn in an iterative way; based on identification of significant issues and the evaluation of these for completeness, sensitivity and consistency, preliminary conclusions can be drawn. Conclusions indicate whether the questions that were posed in the formulation of the goal definition can be answered by the LCA, (e.g., whether significant differences exist between alternatives, which role the various sensitive issues play for such differences, etc.). Subsequent additional checks include: checking whether the preliminary conclusions are in accordance with the requirements and limitations of the goal and scope phase, and checking the limitations of the life cycle inventory phase and the limitations of the life cycle impact assessment phase.

When an LCA is intended to be used in comparative assertions intended to be disclosed to the public, the ISO 14044:2006[148] standard also requires that the evaluation element includes interpretative statements based on careful sensitivity analyses.

Recommendations based on the final conclusions of the LCA must be logical, reasonable and plausible, founded in the conclusions, and strictly relate to the intended applications as defined in the goal of the study. To avoid misinterpretations by the target audience, any relevant limitations are to be given jointly with the recommendations.

B6. Reporting of results

The results and conclusions of the LCI/LCA shall be completely and accurately reported, without bias to the intended audience. The results, data, methods, assumptions and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report shall also allow the results and interpretation to be used in a manner consistent with the goals of the study.

Good reporting of LCI and LCA studies provides the relevant project details, the process followed, approaches and methods applied, and results produced. This is essential to ensure reproducibility of the results and to provide the required information to reviewers to judge the

[147] Refers to ISO 14044:2006 chapter 4.5.4
[148] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=38498

quality of the results and appropriateness of conclusions and recommendations (if included). The complete reporting should also contain the data used and should ensure transparency and consistency of all the methodologies and data employed. It should constitute the primary input to the scientific/technical audience and be a base from which summary reports to other target audiences could be prepared.

Confidentiality interests around sensitive or proprietary information and data are to be met, while confidential access to at least the reviewers is to be granted to support the review of the data set and/or report. Separate, complementary confidential reports can serve this purpose.

In accordance with the ISO 14044:2006[149] standard, this handbook operates with three levels of the classical reporting with different (increasing) requirements:

- Internal report: report for internal use only and not intended for disclosure to any external party outside the company or institution that has commissioned the study or performed the LCA work;
- Third party report: this report is intended to document and/or communicate the results of the LCA to a third party (i.e., an interested party other than the commissioner or the LCA practitioner performing the study). The third-party reports shall include an executive summary for non-technical audience, a technical summary for technical audience and LCA experts, and a main report moving along all the phases of the LCA. It also shall include an annex providing all assumptions made and full LCI results;
- Report on comparative studies to be disclosed to the public: this report shall be produced if the study involves a comparison of products and the results are intended to be disclosed to the public. In addition to the requirements set for the third party report, additional requirements apply[150].

Extensive guidance is available on critical review in the “General Technical Guidance for Integrating Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) into Waste Management” and the ILCD Handbook[151] – General guide, Chapter 11.

B7. Critical review of results

The independent critical review of life cycle assessments is strongly recommended. Under the ILCD Handbook, critical review is required for studies that are reported to third parties and the public.

The critical review is one of key features in the LCA. It shall confirm whether, among others:

- The methods used to carry out the LCA are consistent with the ILCD Handbook and thereby also with ISO 14040 and ISO 14044;
- The methods used to perform the LCA are scientifically and technically valid;
- The data used are appropriate and reasonable in relation to the goal of the study;

[149] Available online at http://www.iso.org/iso/catalogue_detail.htm?csnumber=38498
[150] ILCD Handbook, “General guide for Life Cycle Assessment – Detailed guidance,” Chapter 10.3.4, http://lct.jrc.ec.europa.eu/publications
[151] http://lct.jrc.ec.europa.eu/assessment/projects

- The interpretations reflect the limitations identified and the goal of the study;

Critical review helps to verify that assessments are scientifically and technically robust and that the findings are analysed and reported in an objective, unbiased and transparent fashion. In particular, review provides a mechanism for ensuring the conclusions drawn are appropriate to the scope and depth of the analysis performed. As such, an independent, external and qualified review can provide a useful means of increasing the gravitas of the conclusions reached in the study and their application. Such a review substantially increases the value of a study and is the basis for acceptance, especially if used in public discussions or decision support.

For LCA studies, a qualified, external and independent review is generally required. For macro-level studies this will include a review panel and involve interested stakeholders from the on-set of the study. Stakeholders are also involved in micro-level studies if these include comparative assertions. The “ILCD handbook – Review schemes for LCA” provides an overview of the appropriate review type for LCI data modelling, LCA studies, and some direct LCA applications.

Annex C – Key LCA concepts, strengths and weaknesses

C1. System boundaries and what to include in them

The LCA system boundary is the interface between the waste management system and the environment or other systems. It defines which activities across the life cycle are included within the LCA – where the assessment starts, where it ends and what is included, or excluded, along the way.

Life cycle stages can only be excluded from an assessment if they are either too small to be significant in the assessment, or if they are likely to be common across all the options being considered.

There are two typical cases for waste management LCAs:

1. **Waste management system without prevention, re-use, recycling or recovery actions**. If all waste management options do not include prevention, re-use, recycling, or recovery, activities that occur "upstream", or before the material enters the waste stream (e.g., producing and using the materials) can be excluded from the assessment, because they are common to all options for waste management (i.e., they will have been produced and used in the same way, and no differences in replacing virgin material by recycled material occur);
2. **Waste management system with prevention, re-use, recycling or recovery actions**. If at least one of the investigated waste management options does include measures for prevention, re-use, recycling or recovery, activities that occur upstream in the life cycle of the materials considered must be included. This is because they are likely to be affected by prevention, re-use, recycling or recovery actions, and so could differ for different management options.

Using a wider system boundary when assessing measures for waste prevention, re-use, recycling or recovery means that LCAs tend to be more complicated, but this should be seen as an appropriate reflection of a complex reality. To make things simpler, some of the upstream activities can be excluded if they are not affected by the activities, or if changes are negligible and do not affect the results. For example, if flame retardants are replaced by less hazardous products without affecting the weight or means of application, the transportation and application of the retardant can be left out.

Caution is warranted when making exclusions like this, and system boundary choices should always be scrutinised to ensure that they do not bias the results of a study. The system boundary should always be consistent with the scope of the study and its intended use. Otherwise, the results may not support the decisions that need to be made.

C2. Comparing management options

To avoid bad decisions, or potential accusations of bias, it is important that any comparison is made on an equitable basis. The basis for an equitable comparison is termed the functional unit. So, if an LCA claims that option A has lower greenhouse gas emissions or water consumption than option B, it is only meaningful if both options perform the same function (or functions) using the same functional unit, e.g., the management of projected waste from site X in one year. It may be necessary to consider subsidiary functions provided by one management option, but not by another.

Just as important, fair comparison is only possible provided that LCAs have been conducted with the same scope and objectives. This is why it has been said that LCA can be used to produce the results you want. For example, if you omit the life cycle phase with the highest burdens, you can make an option look better than is warranted. This is one of the reasons why there are ISO standards for LCA, to which any reputable LCA adheres.

In some cases, one waste management option may perform better across all flows in the inventory and for all impact indicators. This option is clearly preferred to other alternatives. However, in most cases no one scenario will out-perform the others in all categories. Frequently, each alternative has advantages and disadvantages and, although the user is informed about the relative environmental costs and benefits of the different options, a choice between them still has to be made.

This choice hinges on the relative importance of the impact categories. There are various techniques that can assist in making such choices, such as normalising different impacts to a common point of reference (e.g., a percentage of per capita impacts for that category), or applying a weighting to the different types of impact. The ILCD Handbook provides further detail on these techniques.

C3. Lifespan and performance of re-used products/materials

It is important to consider a product’s lifespan and its performance when assessing re-use options.

Determining the lifespan of the re-used product or material. The advantage of re-using a product, or material, is that its lifespan is extended and new materials do not have to be produced over that time. Ultimately, the product will reach the end of its life but, by re-using it, new production is avoided for a period. So, the benefit of an increased lifespan should be accounted (not only for waste prevention, but including the benefit of avoiding it altogether).

Taking account of the use of the product or material. For products that use consumables (water, detergents, energy, etc.), the use phase can be an important consideration in the assessment of re-use options. The re-used product will reduce the need for the production of a new item, but the re-used product may not perform as well because of technology improvements and increased efficiencies. For example, re-using refrigeration equipment or boilers may mean that you are using much less efficient equipment than if you used new models.

C4. LCI modelling principles: attributional and consequential

This section refers to the ILCD Handbook[152], General guide for Life Cycle Assessment – Detailed guidance, Chapter 6.5.2. It expands the information given in Chapter 8.1 of this document.

Attributional modelling

The attributional life cycle inventory modelling principle is also referred to as "accounting", "book-keeping", "retrospective", or "descriptive" (or sometimes and potentially confusing: "average" or "non-marginal"). It depicts the potential environmental impacts that can be attributed to a system (e.g., a product) over its life cycle, i.e., upstream along the supply-chain and downstream following the system's use and end-of-life value chain. Attributional modelling uses historical, fact-based, measureable data of known (or at least know-able) uncertainty, and includes all the processes that are identified to relevantly contribute to the system being studied.

In attributional modelling the system is modelled as it is or was (or is forecasted to be). This also applies to its background processes: as background data, producer-specific LCI data is ideally used where specific producers provide a background good or service (e.g., a single tier-two supplier is producing the required bricks for a large office building). Average or generic data are typically used where the goods and services stem from a wide mix of producers or technologies (e.g., for electricity consumed by a consumer product in Austria the regional consumption mix of electricity with the actual quantitative share of power plants using hydro-power, natural gas, hard coal, fuel-oil, nuclear power, biomass, etc., would be used, including the specific electricity imports and exports to/from the regional market; the region in that case might as well be the corresponding region of Austria, whole Austria or Europe). The change from specific to average or generic data is only done for practicality reasons and is a simplification that is justified from the averaging effect that typically occurs several steps up and down the supply-chain and value chain.

Consequential modelling

The consequential life cycle inventory modelling principle is also called "change-oriented," "effect-oriented," "decision-based," "market-based." It aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analysed system's background system and on other systems. It models the analysed system around these consequences. The consequential life cycle model is hence not reflecting the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that is prognostizised along market-mechanisms, and potentially including political interactions and consumer behaviour changes.

To better reflect market constraints and supplier-related explicit decisions, some researchers constrain the market-mechanism models by explicitly considering existing supply-contracts and planned future suppliers. Other constraints in use are existing or expected policy measures such as green taxes / incentives and material bans.

[152] Available online at http://lct.jrc.ec.europa.eu/publications

A key step in consequential modelling is identification of the marginal processes, i.e., the generic supply-chain, starting from the decision and building the process chain life cycle model around it. Some experts identify each one single marginal process; others identify a combination of several of the most likely marginal processes to have a more robust estimate.

A wide range of mechanisms is discussed among LCA practitioners, including how a decision affects other processes and products, and which type of consequences follow. These mechanisms range from causing the need to build new production plants for required additional materials, parts, etc. (or taking plants out of operation), to market displacement of competing products and consumer behaviour changes. Secondary consequences may counteract the primary consequences (then called 'rebound effects') or further enhance the preceding consequence.

Components of general (and in some cases partial) equilibrium models are employed to model the main market consequences. Central in modelling market consequences is a quantitative understanding of the markets and how direct and indirect changes in supply and demand of the analysed good or service act in the markets to cause specific changes in demand and supply of other goods and services.

C5. LCI approaches for solving multifunctionality

This section refers to the ILCD Handbook[153], General guide for Life Cycle Assessment – Detailed guidance, Chapter 6.5.3 and ISO 14040:2006[154] Chapter 4.2.3.1. It expands the information given in Chapter 8.1 of this document.

1st approach: Subdivision of multifunctional processes

“Subdivision” of multifunctional processes refers to the collection of data individually for those of the mono-functional processes that relate to the analysed system and that are contained in the multifunctional process. Subdivision is frequently possible to avoid allocation for black box unit processes; see figure below (Figure 18).

Consequently, the required processes are cut free and the multifunctionality problem is solved, providednone of the included single-operation unit processes is still multifunctional. However, even then the data accuracy has been improved, often substantially. Note that in principle, subdivision is the only correct / exact solution under attributional modelling to solve multifunctionality of further sub-dividable processes; the 'short-cut' of allocation of black box unit processes will often result in distorted inventories, as explained in the text.

Under consequential modelling subdivision is also applicable[155].

[153] Available online at http://lct.jrc.ec.europa.eu/publications
[154] http://www.iso.org/iso/catalogue_detail.htm?csnumber=37456
[155] However, it could be argued that the logic of consequential modelling might require accounting for synergies and other interrelations of processes that operate, e.g., on the same site. This foreground-system internal interrelations and consequences need further methodological clarifications. Similarly, the synergies on site-level might even need to be considered in attributional modelling by an allocation of synergies. For exmaple., a small steam-consuming process on a site may benefit from a big steam-consuming process that has led to the installation of a very efficient steam generating process.

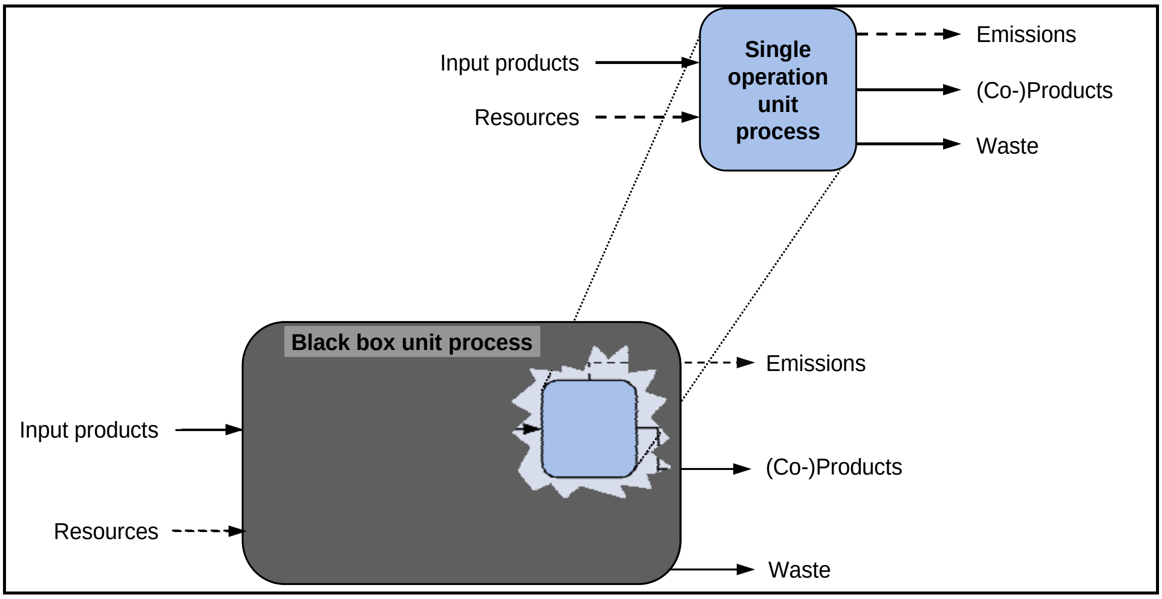

Figure 18: Subdivision of multifunctional processes

2nd approach: System expansion / substitution

“System expansion” and its variant “substitution” are also called “system enlargement” and “crediting" / "avoided burden approach,” respectively. This is a combined concept for ensuring the equality of multifunctional systems. Systems expansion and substitution are mathematically equivalent, as shown in the figure below (Figure 19).

In practice, two different situations can be encountered. The first one is to solve the multifunctionality by expanding the system boundaries and substituting the not required function with an alternative way of providing it, i.e., the process that the not required function supersedes (“substitution”).

The other situation is when several multifunctional systems (e.g., different brands of a complex consumer product) are to be made comparable in a comparison study. This would be done by expanding the system boundaries and adding for the given case missing functions and the inventories of the respective mono-functional products.

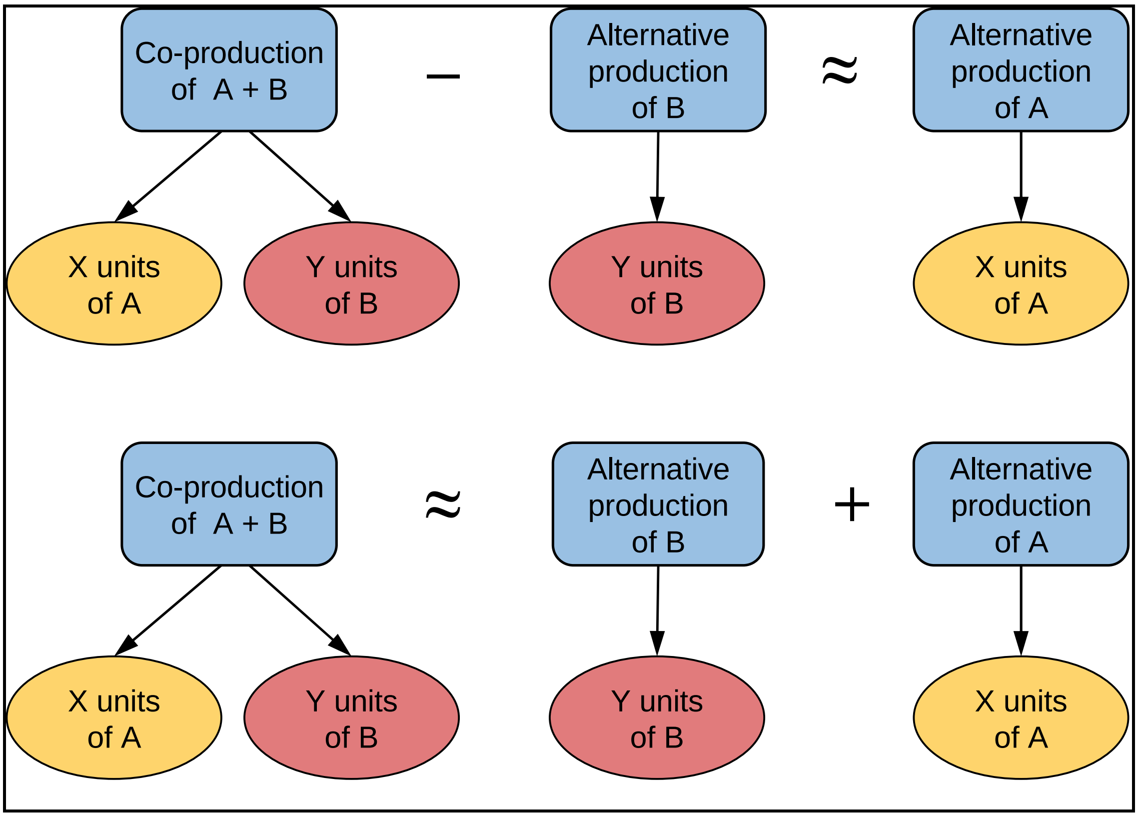

Figure 19: System expansion and substitution

System expansion and substitution are the corresponding method approaches under consequential modelling for solving multifunctionality. However, substitution is also applicable for attributional modelling that is interested to include existing interactions with other systems.

Substitution means to subtract the inventory of another system from the analysed system. This often leads to negative inventory flows. It can even result in negative overall environmental impacts for the analysed system. This means that there is a net benefit of producing the analysed system as the overall impact is more than compensated by the avoided impact the co-functions have elsewhere. This is the correct interpretation, if made within the assumptions of the study, including on the amount of co-functions produced.

3rd approach: Allocation

“Allocation,” also called “partitioning,” solves the multifunctionality by splitting up the amounts of the individual inputs and outputs between the co-functions according to some allocation criterion, being a property of the co-functions (e.g., element content, energy content, mass, market price, etc.); see figure below (Figure 20).

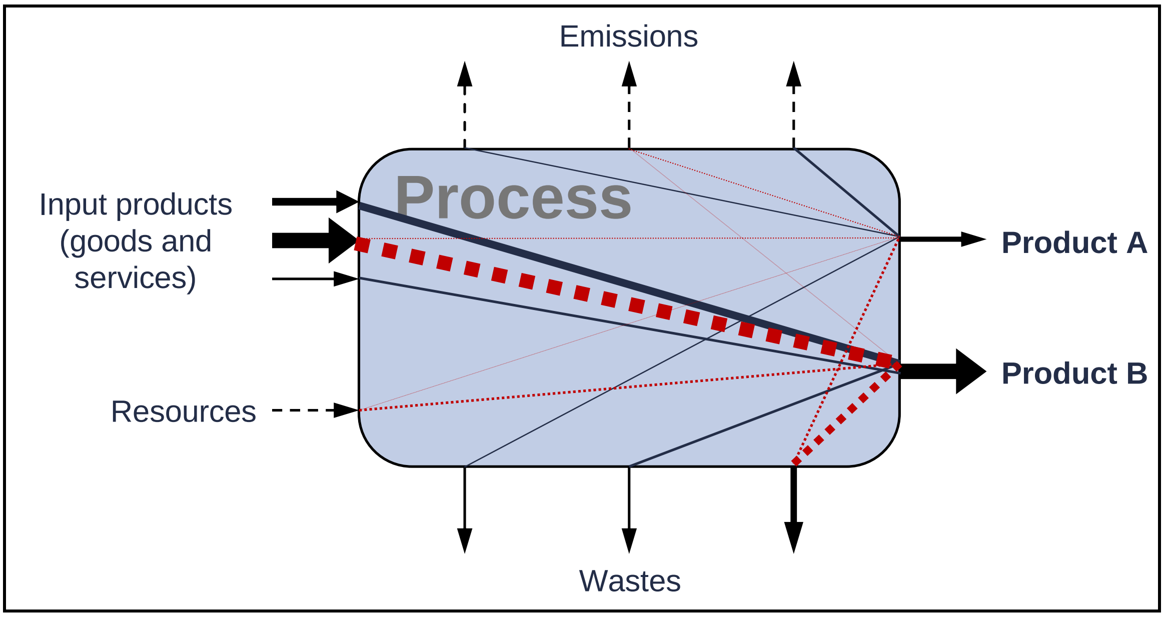

Figure 20: Allocation

The thickness of the lines inside the process indicates which share of each non-functional flow is allocated to each of the two co-functions (here: "Product A" and "Product B"). The flows can be quantitatively allocated to only one (blue, solid lines) or to several (red, dotted lines) of the co-functions. Different allocation criteria can be applied that need to be appropriately identified. The sum of the allocated amount of inventory flows shall be identical to the un-allocated inventory of the process.

If possible, according to ISO 14044:2006, allocation should be performed in accordance with the underlying causal physical - and implicitly also covered: chemical and biological - relationship between the different products or functions. This should reflect the way in which the individual inputs and outputs are quantitatively changed by quantitative changes in the multiple functions delivered by the process or system. When it is not possible to find clear common physical causal relationships between the co-functions, ISO 14044:2006 recommends performing the allocation according to another relationship between them. This may be an economic relationship or a relationship between some other (e.g., non-causal physical) properties of the co-functions, such as energy content that is often used in the allocation between different fuels co-produced in a refinery[156].

Note that if subdivision cannot provide exclusively mono-functional unit processes that can be attributed to the analysed function, allocation is the corresponding method approach under attributional modelling for solving multifunctionality of processes.

C6. Assessing the impacts and benefits of energy recovery

Various parameters can significantly influence the scale of these savings and affect the environmental comparison between energy recovery and other levels of the waste hierarchy (e.g., recycling and disposal). These include:

[156] Note that the use of, the lower calorific value for allocation across refinery products for the black-box unit process refinery is not a causal physical relationship, but a simplified allocation of a non- causal physical relationship in the sense of ISO.

- **The amount of energy recovered** and the part of it which is actually used (or valorised) - or "net efficiency" of the process. This is heavily influenced by whether the energy recovery process generates heat or electricity, or both; and
- **The type of fuel that it replaces -** for example, coal-based electricity or electricity from renewable sources.
- **How the replaced energy has been produced** – e.g., electricity produced in combination with heat (CHP), energy produced at old plants or very efficient ones.

A **substitution approach** can be used to quantify the benefits of energy recovery – in the same way as for recycling. "Avoided burdens" need to be identified by considering what the alternative means of energy generation would be. For locally used heat, the specific alternative heat technology and energy source will be substituted; for electricity inserted into the grid, the national grid mix would be substituted.

Several other factors can also affect the environmental performance of an energy recovery facility, and these should be considered when undertaking an LCA study:

- ***Type of abatement technology.*** The type of abatement equipment employed by an energy recovery facility can add to the energy used by the process. The nature of the feedstock will also be influenced by the type and quantity of chemicals and other materials used to remove pollutants.
- ***Fate of residues and metals.*** Ferrous and non ferrous metals can be recycled at the grate or from the bottom ash produced. Following the principle of substitution as described above, the recovery of metals for recycling will result in significant environmental benefits. Bottom ash can also be open-loop recycled into construction products.
- To limit the potential for burden shifting, the ***fate of toxic metals*** (e.g., heavy metals) resulting from the residues of thermal treatment (bottom ash and air pollution control residues) should be considered. For instance, toxic substances can leach from ash over an extended timeframe if deposited in landfill or within a construction product.

Because of these sensitivities, it is recommended that a "*transfer coefficient*" approach be used in modelling thermal treatment technologies. In this, the performance and residues of energy recovery processes are responsive to the nature of the waste stream that is treated.

The European Reference Life Cycle Database (ELCD)[157] contains data on incineration that uses a transfer coefficient approach.

Emissions to air from energy recovery process

The risks posed to the environment by hazardous substances contained within waste streams suitable for combustion must be carefully modelled in life cycle studies. For example, "treated" creosoted wood has the potential to contribute to the generation of toxic emissions such as dioxins when they are burnt. Heavy metal additives and chlorine contained within plastics and naturally-occurring heavy metals contained within some types of wood also have this potential to contribute to toxic emissions from the stack of energy recovery processes. In many instances, regulatory (feedstock) restrictions can be applied to energy recovery processes to reduce the potential for such problems. In other instances, additional air emissions abatement equipment may

[157] http://lct.jrc.ec.europa.eu/assessment/data

be necessary, whose additional operational impacts/benefits should be considered in the LCA.

To burn or not to burn?

Materials such as plastics possess a high calorific value, suitable for thermal treatment. However, from a life cycle perspective, a higher benefit can be expected from recycling plastics, as long as they underwent limited aging and soiling. For biodegradable waste, the decision greatly depends on the water content (and hence calorific value): if it is too wet, it should not be burned; if it is relatively dry, the energy recovery aspect can outweigh the compost or biogas benefit. If the biodegradable waste has a high content of pollutants, incineration might be one preferable option, i.e. if the compost or digestate cannot be applied to land.

C7. Key LCA strengths

The main advantage of a Life Cycle Assessment (LCA) is its ability to help quantitatively identify benefits and trade-offs. It helps avoid unwanted shifting-of-burdens:

- Between different stages in the life cycle

  Some specific decisions can impact upstream and downstream life cycle stages (indirect effects). Neglecting these consequences may lead to wrong decisions. LCA helps to identify and quantify those indirect effects, while integrating them with direct effects related to the waste treatment itself.

- Between different types of impacts on the environment (e.g., lowering emissions of toxic pollutants when using flue gas cleaning, but increasing CO_2 emissions due to higher energy consumption)
- Between different regions and generations

In practice, the consistent application of LCA according to harmonised and robust methodology and procedures provides significant advantages:

1. <u>Enabling fair comparisons via a quantitative, performance-base approach</u>: all compared waste management systems need to fulfill the same function(s). Therefore, results are a fair basis for environmental comparisons between different options.
2. <u>Identification of key life cycle stages and activities</u>: LCA shows where in the life cycle specific activities matter, i.e., have the largest contribution, or the highest manageability for environmental improvement. This can help to focus efforts on key stages and processes.
3. <u>Identification of key parameters</u>: LCA helps identify the most influential parameters (e.g., water content for biowaste selected for incineration) and impacts, and the sources of these impacts. Therefore, it helps focus collection of key data and manage discussions relating to key parameters around key benefits and trade-offs.

4. Identification of improvement options: as key sources of impacts are identified, a specific analysis can be performed to manipulate the available parameters to optimize a single technology or an entire waste management system towards reducing the environmental impacts.
5. Learning: Gaining increased knowledge of the interaction of waste management systems and upstream and downstream life cycle stages is a subordinate benefit to the primary goal of the LCA.

C8. Key (sometimes perceived) weaknesses of LCA

1. Lack of appropriate or sufficiently quality-assured LCA data

- Any proper decision support LCA on complex questions requires data / information in order to properly analyse the options; this is not a weakness of LCA. but a characteristic of the question to be answered.
- A variety of sources of data exists. However, as there always remains some uncertainty on some parameter values, a sensitivity analysis should be performed, especially if decisions concern new technologies and could have implications for many years, possibly decades. Sensitivity analysis explores the robustness of conclusions and allows answering the question "for which conditions do my conclusions remain valid?”.
- An often cited problem is the lack of appropriate quality LCA data. However, the issue of data availability and appropriateness is common to all studies that evaluate the environmental aspects of solid waste management options in a quantitative manner and must not be regarded as specific to LCA. Conversely, LCA helps identify crucial data gaps that need to be filled in order to perform a proper evaluation and planning of waste management systems. This fequently requires amending the available data with other data from comparable existing studies, laboratory simulations, model predictions, etc. (see resource directory of the EPLCA[158] and the ELCD[159] for background average EU data and core material and services, as well as the upcoming ILCD Data Network for other quality-assured data from third parties).
- It is normal, and even desirable, that different approaches co-exist for different goals. The key question is to apply the right approach to each specific question and goal situation.
- However, in the past, there have been cases where for the same question in the same context, LCAs yielded diverging results. This is likely due to inconsistency of approaches, inconsistency of individual expert judgements/choices, and inconsistency of data t quality and appropriateness,; none of these is justifiable when conducting a modern LCA.
  This was one of the reasons that led to the standardisation process of LCA, which was initiated in the early 1990s and has resulted in the ISO 14040 standard series. This is currently complemented by the International Reference Life Cycle Data System (ILCD)

[158] http://lct.jrc.ec.europa.eu/assessment/projects
[159] http://lct.jrc.ec.europa.eu/assessment/data

Handbook, a series of technical guidance documents for LCA[160] providing the detailed basis to assure quality and consistency of life cycle data, methods and assessments.

2. LCA is a decision support but not a decision-making tool:

Some people expect LCA will “solve the problem” and “make the decision for them.” This is not the case. There is no “automatism” and LCA does not replace political decisions that need to be made. LCA “only” supports decision-making.

- LCA is comprehensive but not complete. It provides information only on the quantifiable environmental aspects. So, even if the environmental preference is clear, LCA results need to be complemented with legal, economic, social, technical and operational information before sound decisions can be made. The environmental benefits must be weighed against those other aspects.
- LCA does not systematically take all environmental impacts into account with similar detail and reliability. Some impacts are not, or are only partly, captured by LCAs (e.g., radioactive waste, noise, odours but also biodiversity and water scarcity).
- LCA does not necessarily produce a “clear answer” identifying the best option, especially if the alternatives are performing similarly from an environmental perspective. However, even for such cases, the LCA can expose clearly the existing advantages and disadvantages of different options and the trade-offs to which any decision is linked. While some people see this as a weakness of the tool LCA, others see this as an appropriate reflection of a complex reality.
- LCA frequently provides diverging results for different impact categories that lead to the need to weigh impacts against each other. This is however a normal step in any real world decision-making process, to weigh the relevance of different aspects against each other.

However, from the environmental perspective, LCA is the most systematic and comprehensive approach available, and it can and should be systematically complemented with additional information. If LCA is not used, a high risk of overlooking or underestimating relevant environmental issues exists, which could then result in taking inappropriate decisions related to waste management systems.

[160] http://lct.jrc.ec.europa.eu/

Annex D – Developing simplified LCA software tools for waste management

Based on the brief introduction given in chapter 4.3.4, this Annex provides guidance in the development of simplified LCA tools, applied to the general waste management context.

LCT-based software tools for the environmental assessment of waste management systems and strategies need to be based on quality-assured data and might take into account straightforward criteria. To develop software that provides a useful output and is practical to use, a thorough understanding of the intended user and business requirements is necessary. Depending on the user, the software may be used to quantify environmental impacts across the life cycle of a particular waste stream or an entire integrated waste management system.

The software needs to be designed and developed for a given by-product group or waste, focusing on the key issues or criteria to be considered and building on relevant experience/studies/data sets. Non-specific, simplified tools attempting to cover waste in general will not provide sufficiently robust results and these tools should not be used to support important waste management decisions. The software should also have a user-friendly interface, allowing users to vary default technical and management parameters according to their specific situation.

An independent review of the software, the system model, the background data, and the parameters is strongly advised to provide quality-assurance to the users. The "ILCD Handbook - Review schemes for Life Cycle Assessment (LCA)"[161] document includes such review provisions for simplified guides and tools.

LCA software tools should allow users to carry out a complete LCA in a quick and simple manner. If intended for non-LCA experts, they must focus on the most relevant technical and management parameters only. They should not require LCA expertise, and should help users interpret results and identify their limitations. Among the different types of LCA software tools, two main types can be identified:

- **General LCA software, for LCA experts**. These tools allow users to build specific, modular waste collection, management/ storage and treatment process chains. LCA expertise is needed for correct modelling and choice of background data.
- **Process or sector-specific simplified LCA tools, for non LCA expert**. These tools allow users to only enter values for a limited number of key (non-LCA) technical/management parameters. All modelling and data-gathering for the detailed system has already been performed, and is contained within the tool.

It is important to stress that simplification of tools - here for waste management - only works if the application area is sufficiently narrow. Simplified LCA tools for "all" purposes do not provide robust decision support.

The recommendations described in the following sections relate to the second type of software: simplified LCA tools. The main steps that need to be considered during software development are summarised in the figure below (Figure 21).

[161] Available online at http://lct.jrc.ec.europa.eu/assessment/projects

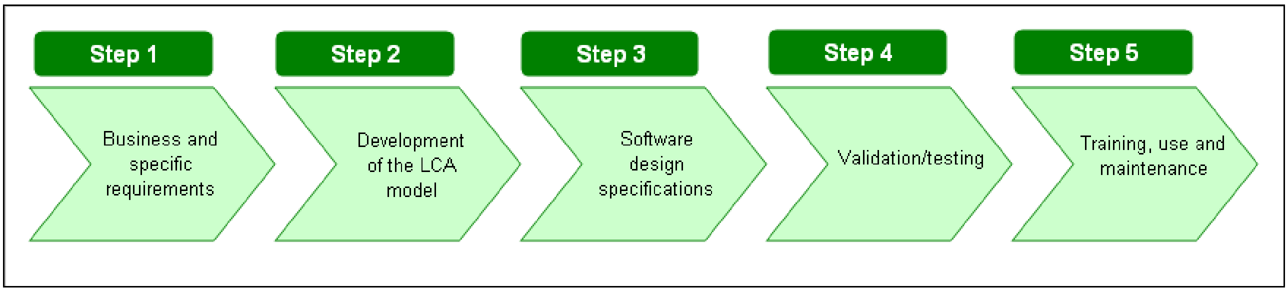

Figure 21: Main steps in software development

Step 1 - business and specific requirements

It is essential that the first step, prior to any software specification or design, is to understand who will use the software and the desired output, as well as what specific requirements are needed to accomplish this.

Business requirements

The business needs for users will be different and they will drive the software specification. A non-exhaustive list of potential software needs for several different user groups is noted below.

For waste managers

- Test and evaluate available waste management options.
- Provide objective information to policy-makers, financial officers and public stakeholders in support of waste strategy options.
- Enhance services: demonstrate environmental improvements for best value and environmental management systems.
- Use as a green procurement tool, as a requirement of tenderers.
- Evaluate tenders for waste management contracts.

For service and technology providers

- Test and evaluate service options: including recovery options, treatments and collection schemes.
- Benchmark environmental performance of new processes relative to other processes.
- Identify potential environmental hotspots or liabilities for a new process.
- Optimise environmental performance.
- Disseminate information to the market.
- Use as a green procurement tool to improve tenders.

For policy-makers

- Provide objective information to policy-makers, financial officers and public stakeholders in support of waste strategy options.

For researchers and academics

- Use as a training tool for students.
- Evaluate new waste technologies.
- Assess the impact of process modifications and changes in technologies.

Specific requirements

Having identified the intended purpose of the tool, the next, essential, step is to define users' needs in more detail. This need mainly applies to:

- The type(s) of waste stream
- The geographical area covered and potential differentiation (local, region, Member State, EU, etc.)
- The envisaged treatment methods and differentiation into specific technologies (screening, crushing, segregation, recycling, incineration, landfill, etc.)
- The specific existing waste treatment infrastructure (to use specific characteristics of this infrastructure in the software)
- The goal of the user (improvement of existing system, new strategic developments, communication to citizens, etc.).

The software tools can range from the very general, usable for many cases (and potentially less relevant or more complex to use) to the very specific, with limited scope of applications (but potentially easier to use). It is important that consideration is given to business and specific requirements to ensure that the most appropriate solution is identified. Otherwise, the outcome may not be fit-for-purpose, or more than is really required.

Step 2 - development of an LCA model

Modularity

A waste management model includes several modules. Each module tackles a specific activity like collection, sorting, storage, transport, etc. The way in which the different activities are grouped into modules is specific to each software tool. For example, screening and crushing, collection and transport can be grouped or not; power production can be included in the incineration module or stand alone. The more specific the modules are, the more flexible the model will be - but more parameters will be required in this instance. The intended use should determine the level of granularity chosen.

Data quality requirements

The choice of the data sources should follow the data quality rules from ISO 14044:2006 and the quality, method, nomenclature, documentation and review requirements of the ILCD Handbook. More specifically, all data sets should meet the ILCD-compliance requirements, being modelled for "Situation A" micro-level applications[162]. This implies that the data are consistent, independently externally reviewed, and have a minimum declared quality. Their specific quality-level depends on their specific influence on the results (i.e., can case-wise range from data estimates to high quality).

ILCD-compliance is specified in the ILCD Handbook - General guide on LCA and referenced documents. The document "ILCD Data Network - Compliance rules and entry-level requirements" provides a systematic overview.

In principle, ILCD-compliance covers method, quality, nomenclature, documentation, and review. “Quality” itself is further subdivided into representativeness (technological, geographical, time-related), completeness, precision/uncertainty, and consistency. These aspects are equally used as quality indicators for each data set and are - as the inventory and data set documentation - subject to independent external review.

Data sources

Unless data sets are specifically collected/developed for the tool, i.e., especially for background data, external data sources are required.

The ILCD Data Network (currently in preparation) aims to be a central access point for ILCD-compliant data from all kinds of primary and secondary data providers. Also, the data sets of the ELCD database are foreseen to be made accessible via the ILCD Data Network (see box below).

The upcoming ILCD Data Network[163]

The upcoming ILCD Data Network is a de-centralised and web-based network that provides consistent and quality-assured life cycle emission and resource consumption data sets (life cycle inventories). The Network is open for all data providers to join and is free to use.

Consistency of the data in the Network from different sources helps to reduce costs and expertise to the end-user, while quality assurance is provided by the link with the Handbook.

European Reference Life Cycle Database (ELCD)

The intention is that the data contained in the European Reference Life Cycle Database (ELCD)[164] will form one component of the ILCD Data Network. The ELCD comprises life cycle inventory data from EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. Its focus is on data quality, consistency, and applicability. The datasets are accessible free of charge.

European Platform on Life Cycle Assessment

The ILCD Handbook/Data Network and the ELCD database have been developed in the context of the European Platform on LCA[165]. This Platform was established by the Commission to support life cycle thinking and assessment in business and policy. The Platform includes a Forum for discussions and an LCA resource directory which provides comprehensive information on LCA services, tools, databases and providers on a global scale.

[162] The simplified tools addressed here aim at supporting regional and local decisions. For waste management analysis on national or supra-national level with consequences on other industries, detailed LCA studies are the more suitable instrument.

[163] http://lct.jrc.ec.europa.eu/assessment/data

Identification of the key parameters

Any model will require both “foreground” and “background” data:

- Foreground data include parameters that are under the direct control, or decisive influence (key parameters), of the waste management and treatment system operator. As such, they should be user-defined in the tool and should include parameters that a user can easily define, such as waste production (t/year), the waste net calorific value or the energy consumption of a specific treatment process.
- Background data are generally used for processes and activities that are not under the direct control of the waste manager/treatment operator. These can be data from the actual supply-chains, market average data, or generic data. If more suitable than available/accessible primary data, such secondary data can also be used for parts of the foreground system; however, the accuracy and precision limitations of the secondary data must be considered explicitly when interpreting the results.

Identification of key parameters should be based upon related findings from existing, detailed studies; details from sensitivity analysis in these studies help identify parameters that need to be kept flexible and those that can be fixed.

Only studies that represent the range of waste treatment and management situations covered by the software, have sufficient quality and are methodologically sufficiently similar to the one implemented in the software should be considered (see "Data quality requirements" above for more). Where necessary and to fill specific gaps, additional analysis or whole studies will be required. This is indispensible to ensure the reliability and robustness of the software. For the waste LCA software, the document “General technical guidance document for integrating Life Cycle Thinking into waste management” provides a first identification of some of the key parameters for each waste management step.

The interface should include the key parameters. They should be determined according to:

- The degree of their influence on the results: results should vary significantly when parameter values evolve;
- The realistic nature of a value change for the parameter: in a region where all the residual waste is incinerated, the repartition incineration/landfilling is fixed (100/0) and should not be an accessible parameter even if results would change markedly if waste was landfilled;
- The probability that the user will want to change the value of this parameter: This probability increases for parameters that the user can change easily (e.g., for waste collection the transport distance and type/size of truck as well as emission standard can more easily be changed than fuel consumption or specific truck emissions).

Ideally, the interface should include viewing options, allowing modification of the list of accessible key parameters. Depending on the needs and the type of user, the list of parameters for which it is possible to encode data could then be extended or reduced.

In order to avoid errors, if no data are encoded,

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[164] http://lct.jrc.ec.europa.eu/assessment/data
[165] http://lct.jrc.ec.europa.eu/assessment/data

- either the most representative/typical data is used by default (and a warning message might be given to the user) or
- a message is shown and the user informed or the calculation could be blocked as long as empty fields remain, for highly variable and influential parameters.

In either case, the lack of data or its accuracy should be considered in the results; calculating reasonably best and worst case scenarios can substantially support this. The user, hence, would need to provide three sets of parameters on most reasonable case, reasonably best and reasonably worst case. See also below.

Presentation of results

The selection of the results presentation format will depend on the target audience and the specific purpose. The form can be graphics, tables or integrated reports, using templates.

To avoid over interpretation by the users of insignificant results, both the uncertainty of the parameters (especially for default values) and of the data sets' inventories themselves should be quantitatively considered. The result of the tool (i.e., calculated impacts or other identification of better options) should be accompanied by information on the uncertainties and the general robustness of the results.

Direct and easy export of textual, numerical and graphical results to typical office software (e.g., Microsoft Office, Adobe) can be considered, as well as the ability to directly print results in a useable format.

Step 3 - design specifications

Although the design specifications for software development are highly dependent on the intended user and purpose, general concepts and design considerations apply to most scenarios. These concepts are summarised in the figure below (Figure 22).

Figure 22: General aspects of design specification for software development

Modularity

Modularity (as earlier noted) refers to the software being designed in multiple individual components. This allows for testing of each independent module for errors as well as ensuring easier maintenance and upgrade capability.

Data structure

The background databases and user input data should be structured in a way that is logical and is clearly linked to the appropriate modules. For example, if there are three modules in the software, it would be useful for the input data to be structured in three corresponding steps. As with the modularity, this will ensure easier maintenance and upgrade capability. Storage of the databases and input data should also be considered at this stage. This will include choosing a server where the information will be hosted and considerations related to server maintenance, availability, accessibility, confidentiality and upgrade needs.

User interface and software architecture

A simple and easy-to-use interface is essential. The user interface can often be broken down to three main components. Each must be developed with user logic and simplicity in mind:

- Data input – data should be easy to input or to upload, and entered in a logical sequence where each step can be plugged in as one parameterised process;
- Calculations and/or data manipulations – should be done automatically where possible and clearly state all background assumptions and limitations associated with them to avoid issues such as unit conversion errors and concerns over transparency; and
- Results/outputs – must be easy to interpret and disseminate.

The format in which results are presented will depend on the target audience and specific purpose. This could be graphics, tables, integrated reports or combinations of these. To avoid over-interpretation of insignificant results by users, both the uncertainty of the parameters (especially for default values) and of the data sets' inventories themselves should be quantitatively considered. The tool’s results (i.e., calculated impacts or identification of preferred options) should be accompanied by information on the uncertainties and the general robustness of the results.

Software accessibility must be considered in relation to the user. Whether the software must be downloaded to a personal computer, accessed from an external drive or via a remote server should be considered in terms of who will be using the software and the resources they will have available to them.

Ease of maintenance and updates

In association with the modular design, the software should allow adding new data for new technologies and additional parameters. It should be anticipated that regular revisions/updates will be undertaken.

Extensibility

New additions to the software should not require fundamental changes to the user interface or overall software architecture.

Security and confidentiality

The software should be designed with the appropriate levels of security settings to protect confidentiality of the data and results.

Input and output compatibility

The software should consider the existing format of the input data to allow for easy transferor upload (e.g., Microsoft Excel format, etc). Direct and easy export of textual, numerical and graphical results to typical office software (e.g., Microsoft Office, Adobe, etc.) should be considered at the design stage; similar consideration applies to having the ability to directly print results in a useable format (e.g., result resembles a summary report).

Software implementation

Implementation refers to the actual coding in a software language that is required to develop the software. Software implementation is a complex task normally carried out by experienced software developers. Alternatively, a user may wish to use a program such as Microsoft Excel. A familiar interface, such as Excel, can simplify the process by allowing a user to avoid the learning curve associated with new software and can also allow in-house skills to be used for updates.

Step 4 - validation and testing

Validation of the software is essential to identify oversights as well as to find errors and miscalculations. Testing should be done by the software developer/commissioner, ideally involving testing by some intended users.

Via a more formal, independent external reviewer, an assurance should be given to the external users that the tool (especially its models and data) meet the specified requirements of quality and robustness. Especially for software that claims to provide ILCD-compliant models and data, the review requirements contained in the document ILCD Handbook[166] – General guide, Chapter 2.3, with the applicable view scheme being specified in the ILCD Handbook – Review schemes for LCA" have to be met.

Step 5 – training, use and maintenance

Training modules should be developed (e.g., manuals, online tutorials, classes or workshops, etc.) to ensure the software is used properly and the functionality is understood by trainees. As waste management data, practices and policy change and develop, it is likely that maintenance to the software will be needed.

[166] http://lct.jrc.ec.europa.eu/assessment/projects

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Abstract

The amount of waste generated in Europe and, beyond, by our production and consumption patterns is significant. A proper waste management is essential in order to reduce detrimental environmental impacts.

For the European Union, the general principles of good waste management are outlined in the Waste Framework Directive (2008/98/EC). This directive establishes a five-step legally binding hierarchy of waste management, starting with the preferred option of waste prevention, followed by preparing waste for re-use, recycling and other recovery, with disposal (such as landfill) as the last resort. The European Commission (EC) encourages the use of Life Cycle Thinking (LCT) to complement the waste hierarchy for a more environmentally sound and factual support to decision-making in waste management. This has led to the development of a set of guidelines, tailored to the needs of different target audiences, which help apply LCT and quantitative tools such as Life Cycle Assessment (LCA) to waste management systems and strategies.

This guide focuses on the most relevant technical aspects that need to be considered when applying Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) to the waste management sector. Main focus is put on the environmental pillar of sustainability. It builds on the International Organization for Standardization (ISO) 14040 and 14044 standards for LCA and the International Reference Life Cycle Data System (ILCD) Handbook and, for LCA in waste management, on the ISO 14040 and 14040 and ILCD Handbook provisions.

It is aimed at waste managers, technicians and LCA practitioners, but also provides policy makers with insights and hints on what they need to consider when using LCT and LCA to support policy making in the waste management context.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

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